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**Drogi et al.**

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(54) **MULTI-LEVEL ENVELOPE TRACKING SYSTEMS WITH SEPARATE DC AND AC PATHS**

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See application file for complete search history.

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(56) **References Cited**

U.S. PATENT DOCUMENTS

6,438,365 B1 8/2002 Balteanu  
6,704,560 B1 3/2004 Balteanu et al.  
6,977,976 B1 12/2005 Birkett et al.  
7,496,339 B2 2/2009 Balteanu et al.  
8,140,028 B2 3/2012 Balteanu et al.  
8,351,873 B2 1/2013 Balteanu et al.  
8,718,188 B2 5/2014 Balteanu et al.  
8,786,371 B2 7/2014 Popplewell et al.

(Continued)

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OTHER PUBLICATIONS

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International Search Report and Written Opinion for International Application No. PCT/US2020/052329 dated Jan. 8, 2021 in 10 pages.

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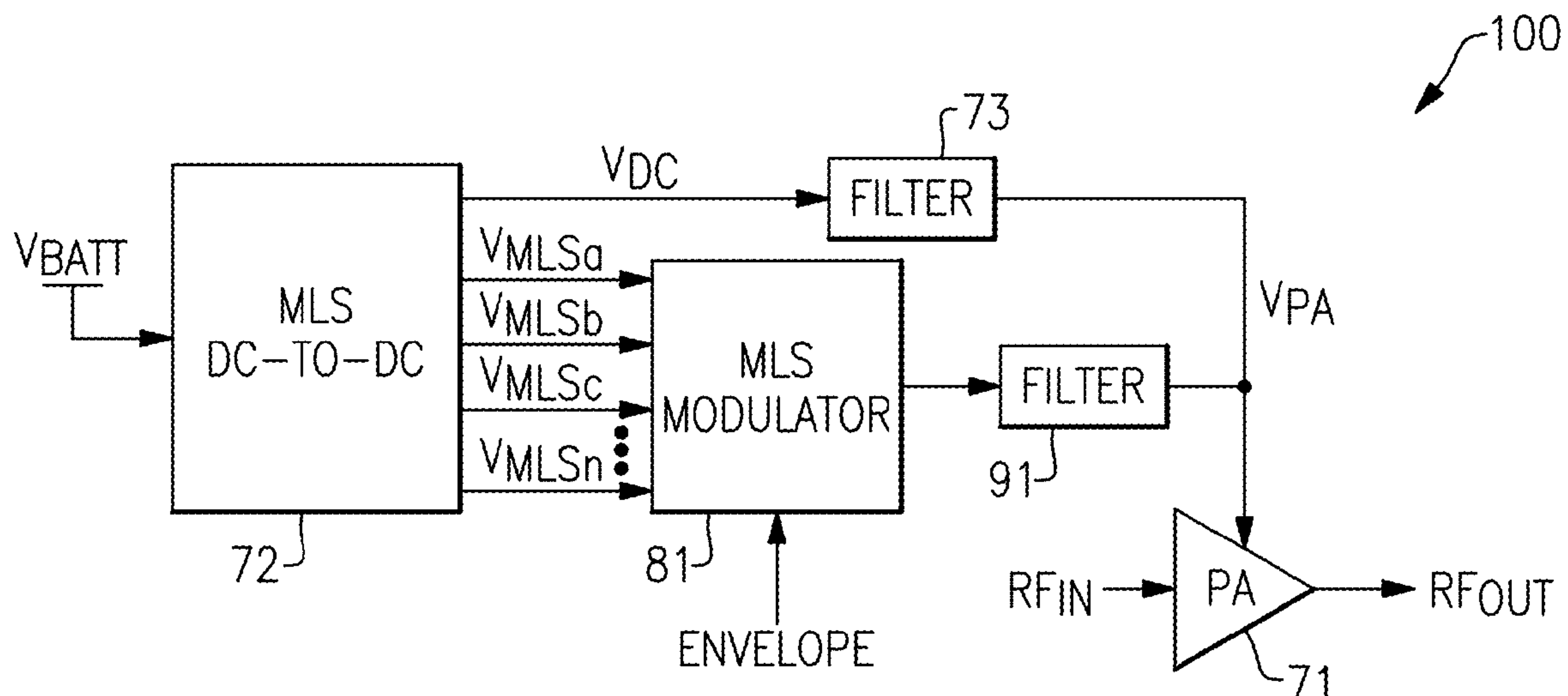
(57) **ABSTRACT**

Multi-level envelope tracking systems with separate DC and AC paths are provided. In certain embodiments, an envelope tracking system for generating a power amplifier supply voltage for a power amplifier is provided. The envelope tracking system includes a multi-level supply (MLS) DC-to-DC converter that outputs multiple regulated voltages, an MLS modulator that controls selection of the regulated voltages over time based on an envelope signal corresponding to an envelope of a radio frequency (RF) signal amplified by the power amplifier, an AC path filter coupled between an output of the MLS modulator and the power amplifier supply voltage, and a DC path filter coupled between a DC voltage and the power amplifier supply voltage.

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**20 Claims, 14 Drawing Sheets**



(56)

References Cited

U.S. PATENT DOCUMENTS

8,866,548 B2	10/2014	Drogi et al.	2017/0195972 A1	7/2017	Drogi et al.
8,981,847 B2	3/2015	Balteanu	2017/0223632 A1	8/2017	Balteanu et al.
9,083,455 B2	7/2015	Popplewell et al.	2017/0228332 A1	8/2017	Ross et al.
9,092,393 B2	7/2015	Whitefield et al.	2017/0338773 A1	11/2017	Balteanu et al.
9,118,277 B2	8/2015	Balteanu et al.	2018/0076772 A1	3/2018	Khesbak et al.
9,143,096 B2	9/2015	Balteanu et al.	2018/0138862 A1	5/2018	Balteanu et al.
9,189,430 B2	11/2015	Ross et al.	2018/0152945 A1	5/2018	Balteanu
9,197,128 B2	11/2015	Popplewell et al.	2018/0159476 A1	6/2018	Balteanu et al.
9,225,308 B2 *	12/2015	Langer ..... H03F 3/19	2018/0159478 A1	6/2018	Balteanu et al.
9,288,098 B2 *	3/2016	Yan ..... H04B 1/0475	2018/0167037 A1	6/2018	Zhu et al.
9,294,054 B2	3/2016	Balteanu et al.	2018/0234095 A1	8/2018	Balteanu et al.
9,391,648 B2	7/2016	Popplewell et al.	2018/0278214 A1	9/2018	Jin et al.
9,425,833 B2	8/2016	Popplewell et al.	2018/0287573 A1	10/2018	Khesbak et al.
9,445,371 B2	9/2016	Khesbak et al.	2018/0294776 A1	10/2018	Popplewell et al.
9,584,070 B2	2/2017	Balteanu et al.	2018/0302036 A1	10/2018	Balteanu et al.
9,588,529 B2	3/2017	Balteanu et al.	2018/0331659 A1	11/2018	Khesbak et al.
9,606,947 B2	3/2017	Ross et al.	2018/0351454 A1	12/2018	Khesbak et al.
9,668,215 B2	5/2017	Balteanu et al.	2018/0375476 A1	12/2018	Balteanu et al.
9,673,707 B2	6/2017	Popplewell et al.	2018/0375483 A1	12/2018	Balteanu et al.
9,698,832 B2	7/2017	Popplewell et al.	2019/0020315 A1	1/2019	Khesbak et al.
9,774,300 B2	9/2017	Jin et al.	2019/0123690 A1	4/2019	Balteanu et al.
9,806,676 B2	10/2017	Balteanu et al.	2019/0158046 A1	5/2019	Lehtola et al.
9,831,834 B2	11/2017	Balteanu et al.	2019/0165736 A1	5/2019	Khesbak et al.
9,876,473 B2	1/2018	Khesbak et al.	2019/0190462 A1	6/2019	Zhu et al.
9,893,682 B2	2/2018	Zhu et al.	2019/0229621 A1	7/2019	Balteanu et al.
9,935,582 B2	4/2018	Balteanu et al.	2019/0341888 A1	11/2019	Drogi et al.
9,948,241 B2	4/2018	Popplewell et al.	2019/0372526 A1	12/2019	Balteanu et al.
9,971,377 B2	5/2018	Balteanu et al.	2019/0372628 A1	12/2019	Balteanu et al.
9,973,088 B2	5/2018	Balteanu et al.	2019/0386617 A1	12/2019	Naraine et al.
9,990,322 B2	6/2018	Whitefield et al.	2020/0067406 A1	2/2020	Khesbak et al.
9,991,856 B2	6/2018	Khesbak et al.	2020/0099343 A1	3/2020	Khesbak et al.
2011/0058601 A1	3/2011	Kim et al.	2020/0112300 A1	4/2020	Balteanu et al.
2012/0269240 A1	10/2012	Balteanu et al.	2020/0127619 A1	4/2020	Khesbak et al.
2013/0207731 A1	8/2013	Balteanu	2020/0154434 A1	5/2020	Balteanu
2014/0184337 A1	7/2014	Nobbe et al.	2020/0162028 A1	5/2020	Balteanu et al.
2015/0236729 A1 *	8/2015	Peng ..... H03F 3/24 455/114.3	2020/0162030 A1	5/2020	Drogi et al.
2016/0028305 A1	1/2016	Kay et al.	2020/0259458 A1	8/2020	Balteanu et al.
2017/0131734 A1	5/2017	Balteanu et al.	2020/0259459 A1	8/2020	Balteanu et al.
			2020/0336110 A1	10/2020	Drogi et al.
			2020/0336122 A1	10/2020	Lin et al.
			2020/0343865 A1	10/2020	Balteanu et al.

\* cited by examiner



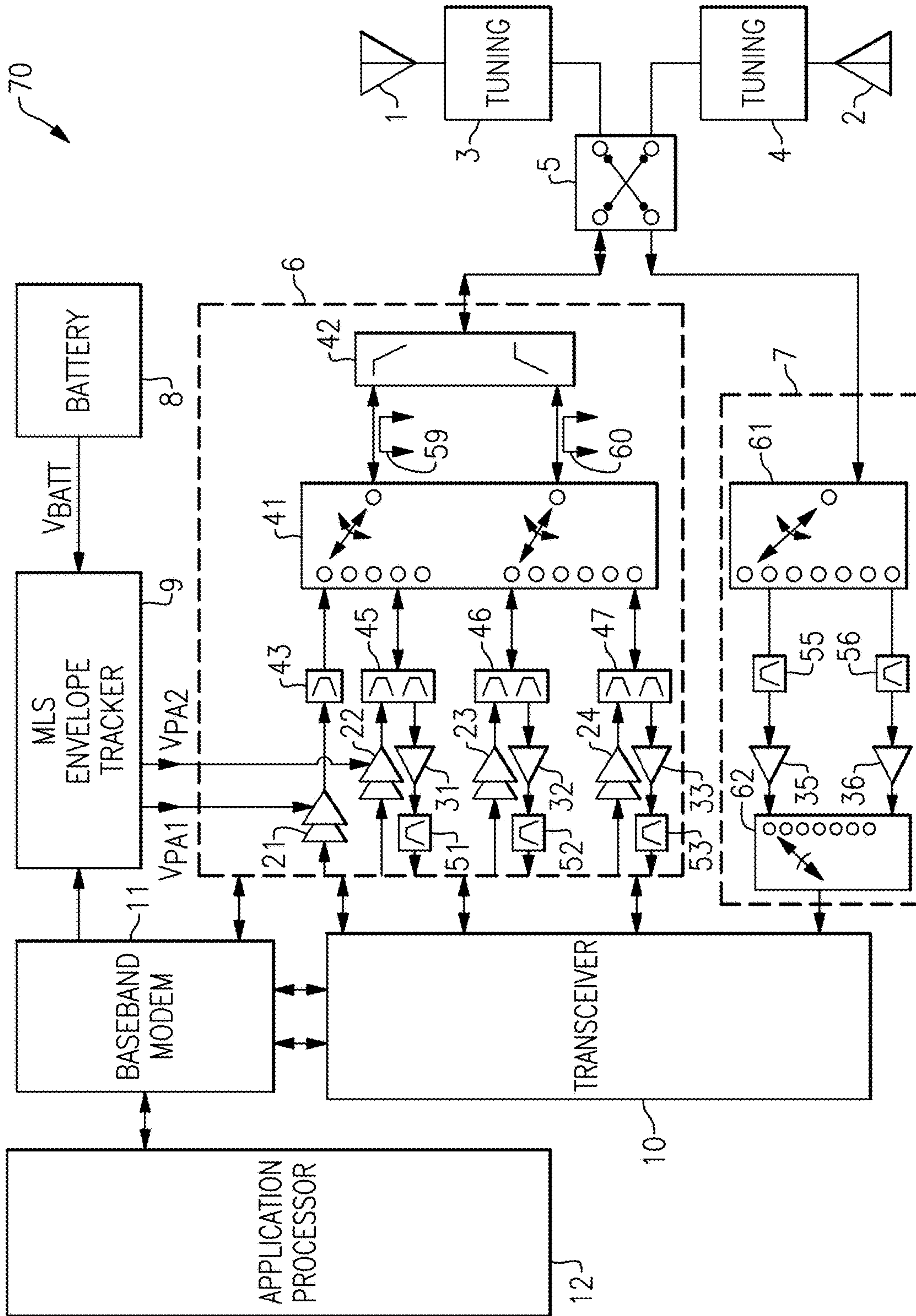
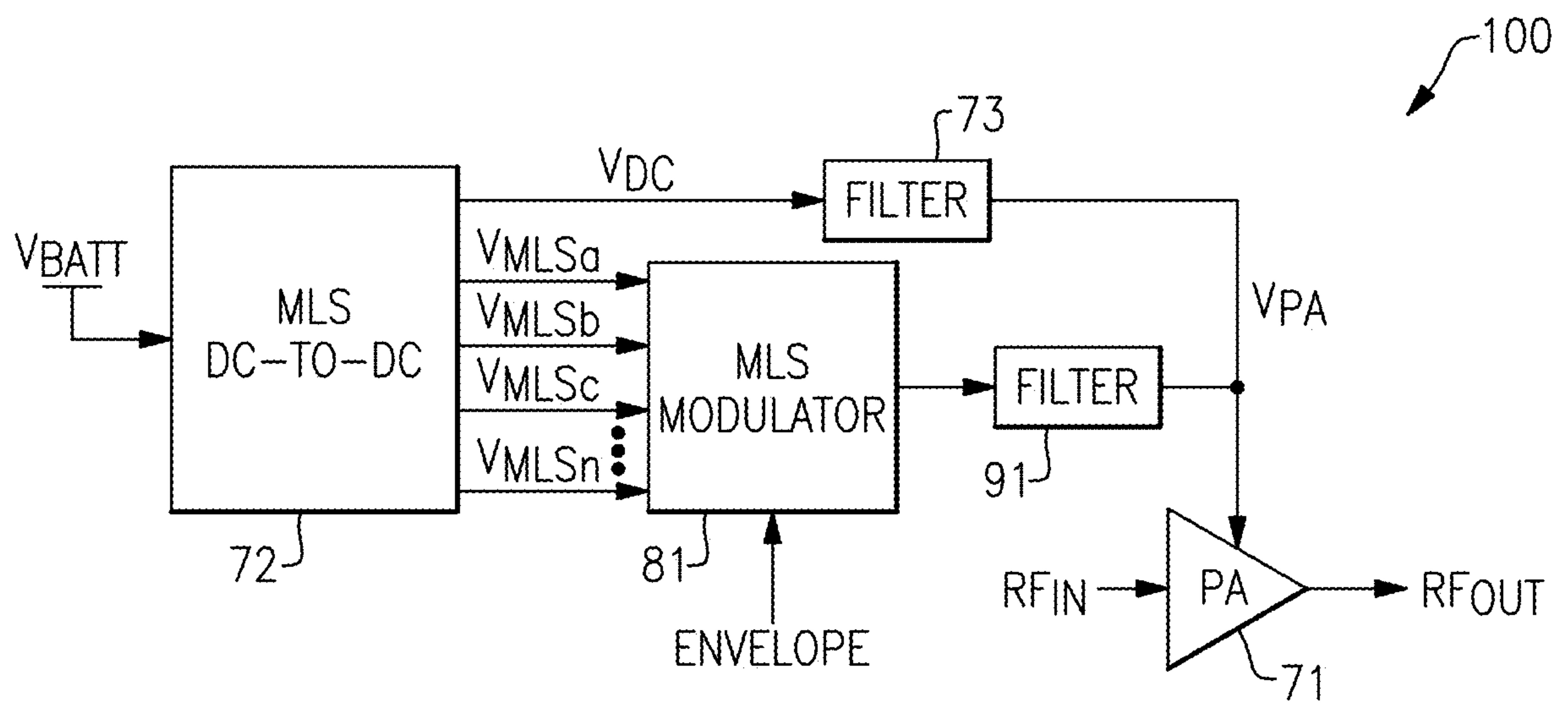


FIG.1



**FIG.2**

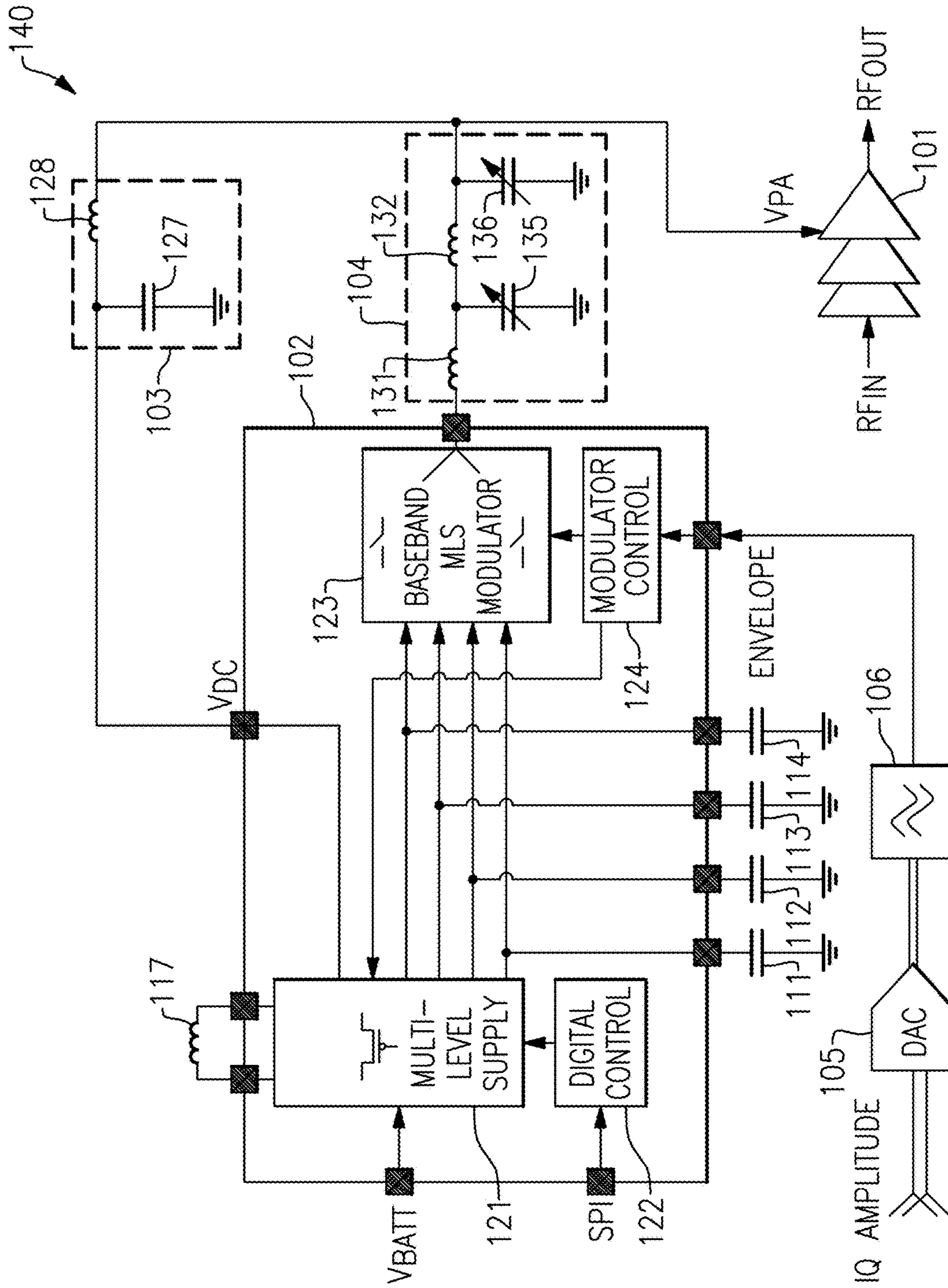


FIG. 3A

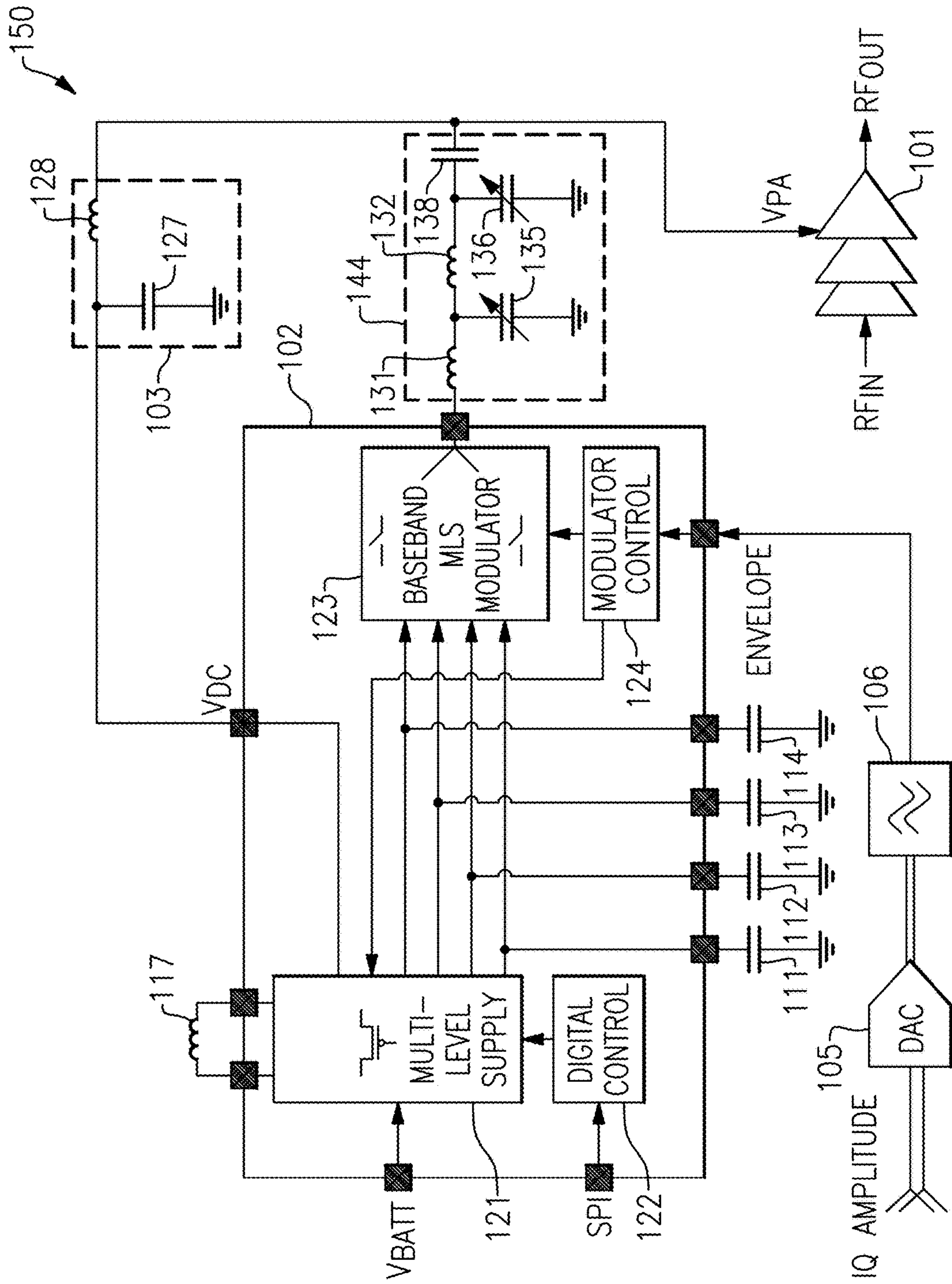


FIG. 3B



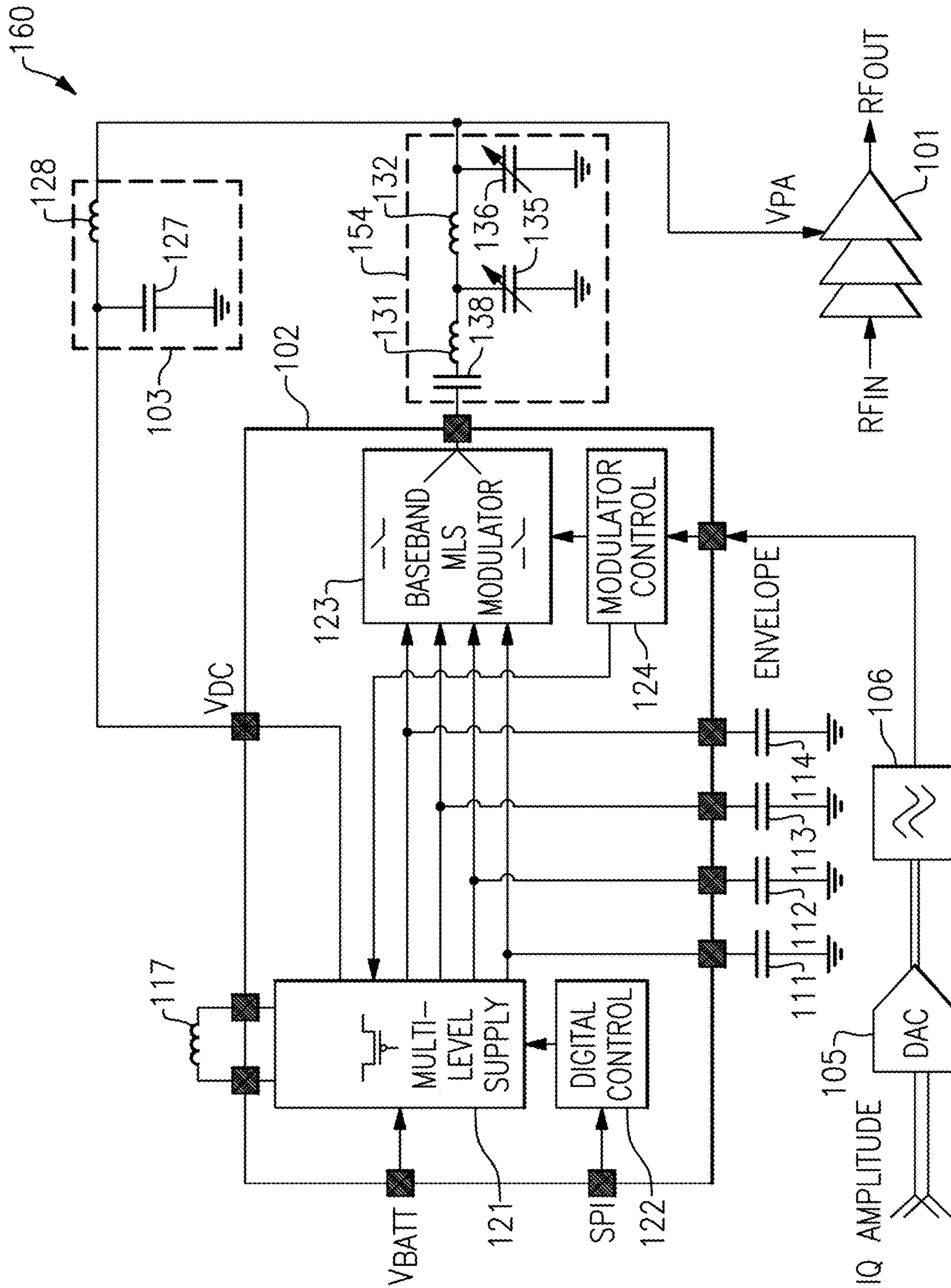


FIG. 3C

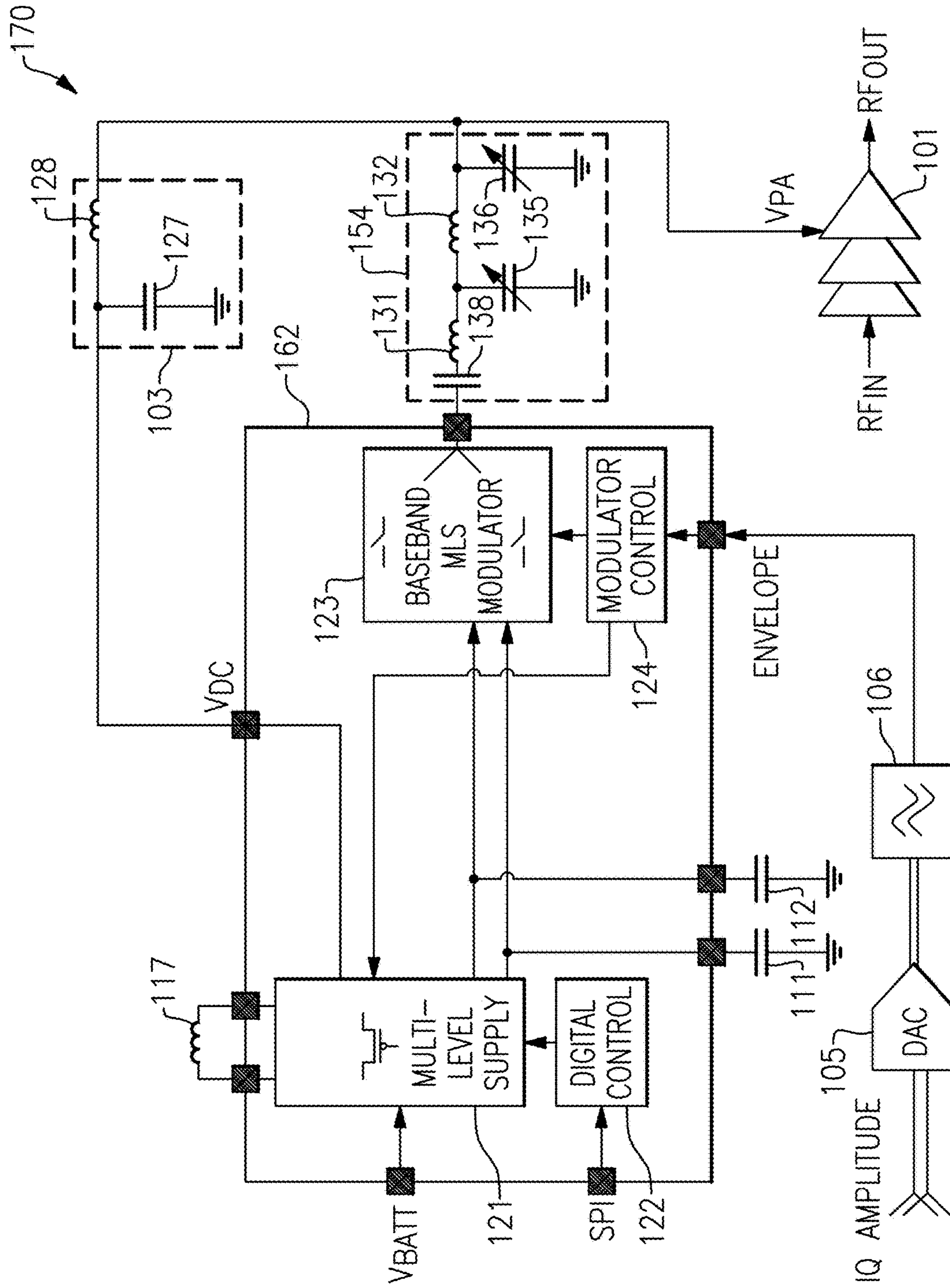


FIG. 3D



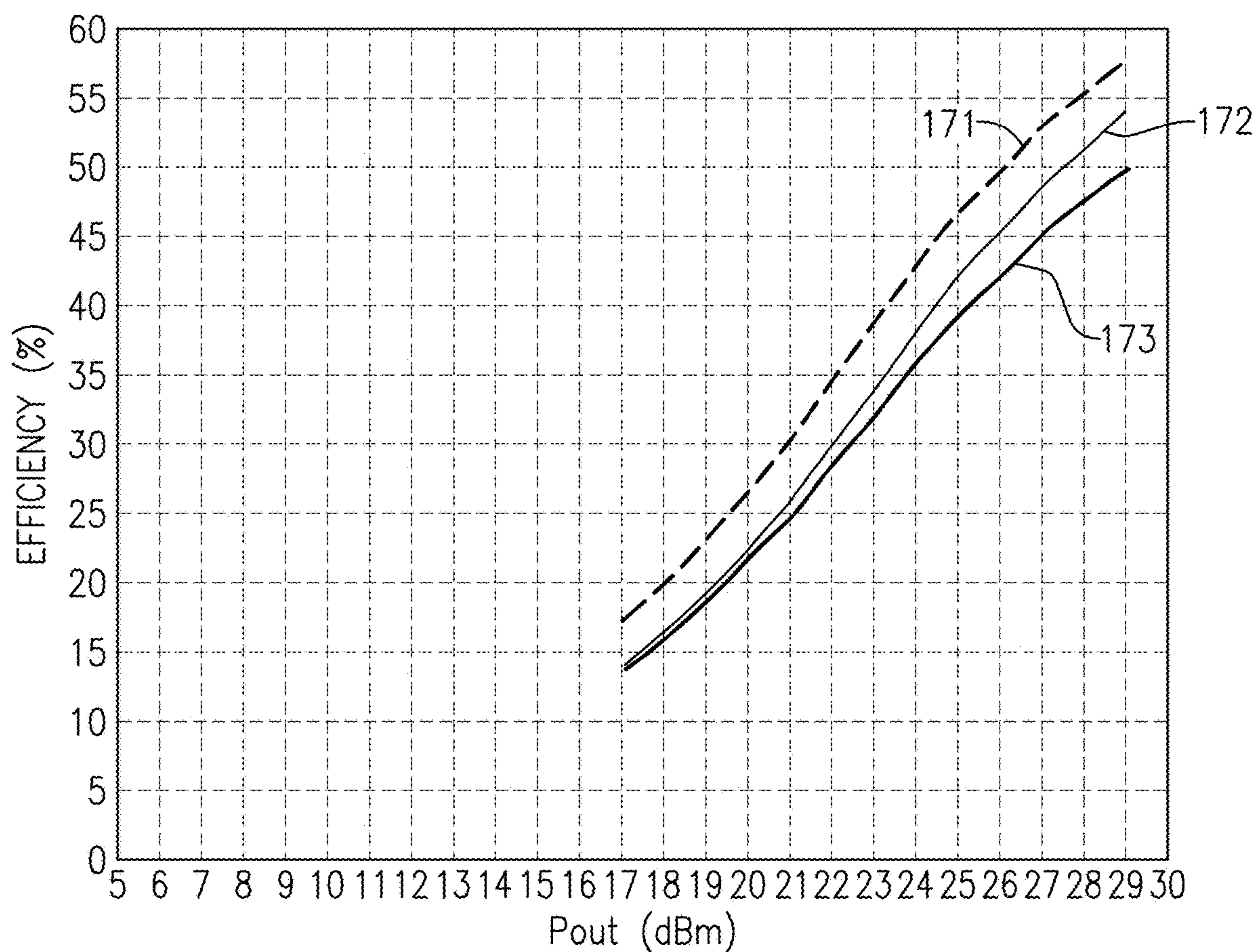


FIG.4

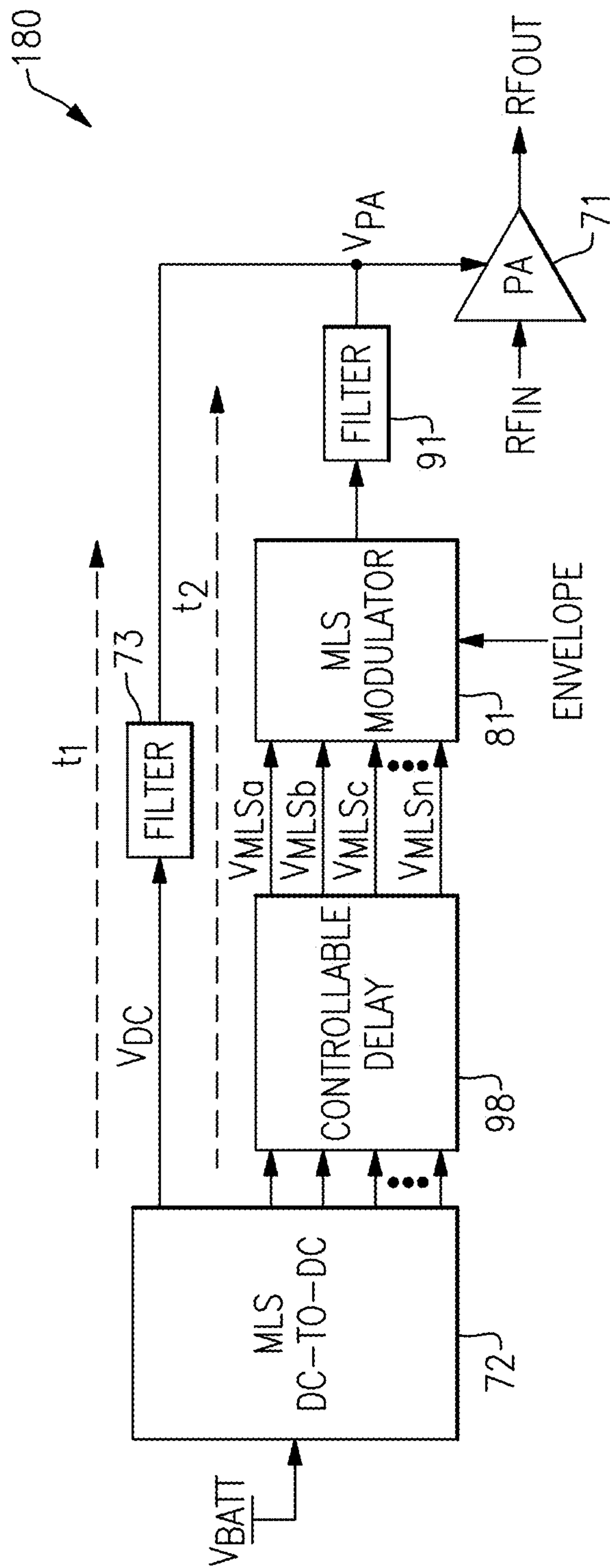


FIG.5





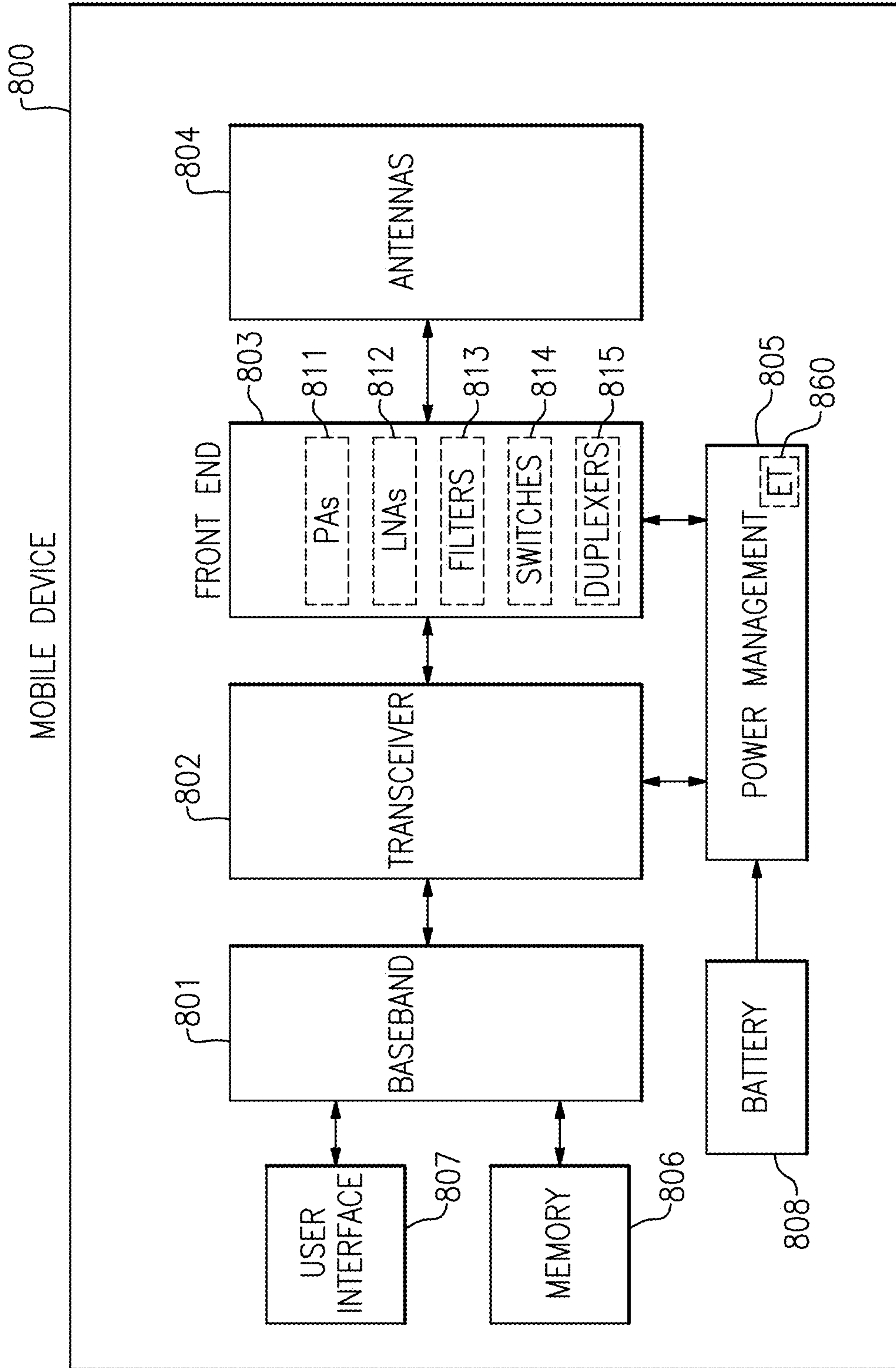


FIG.7

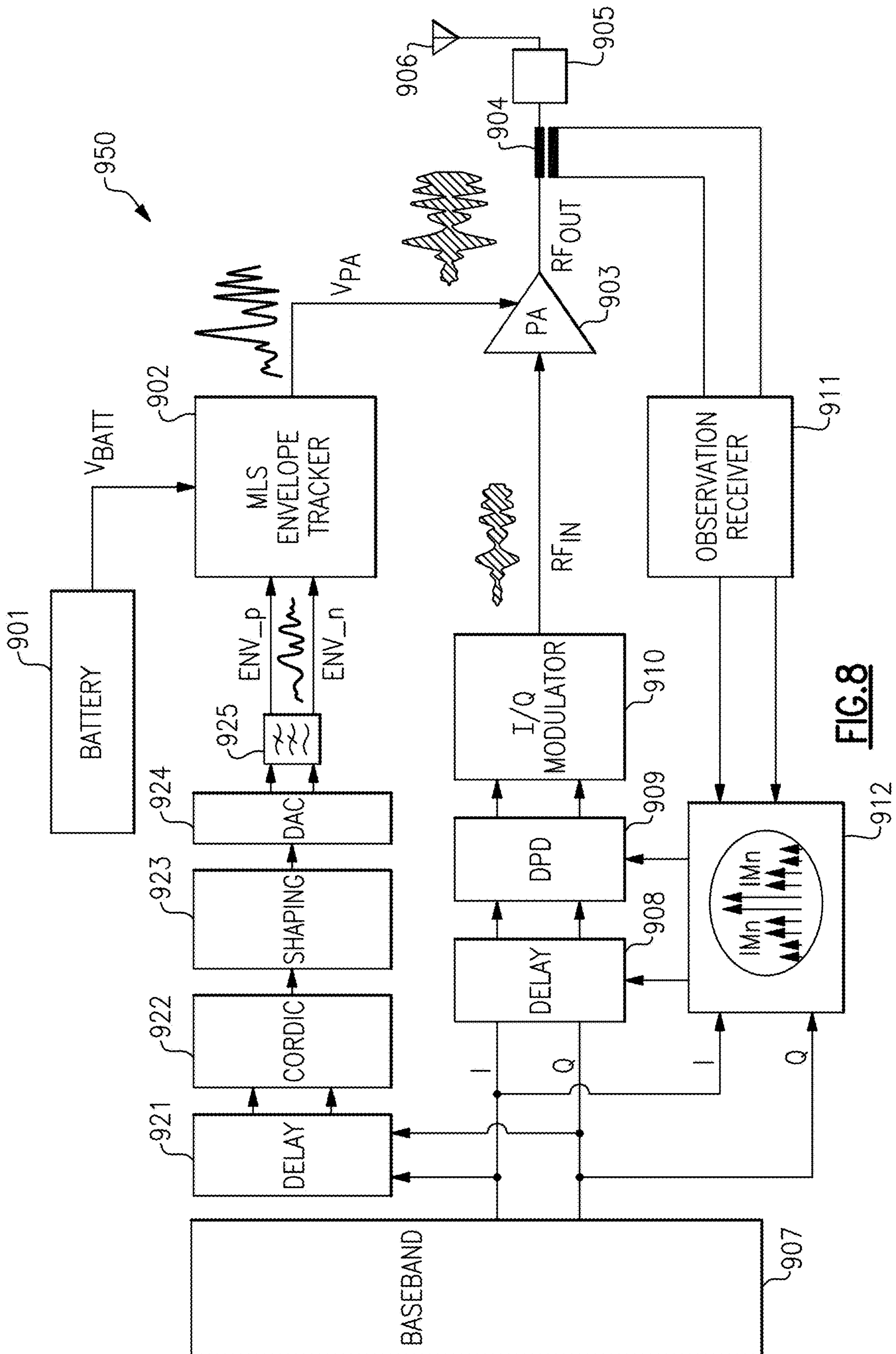
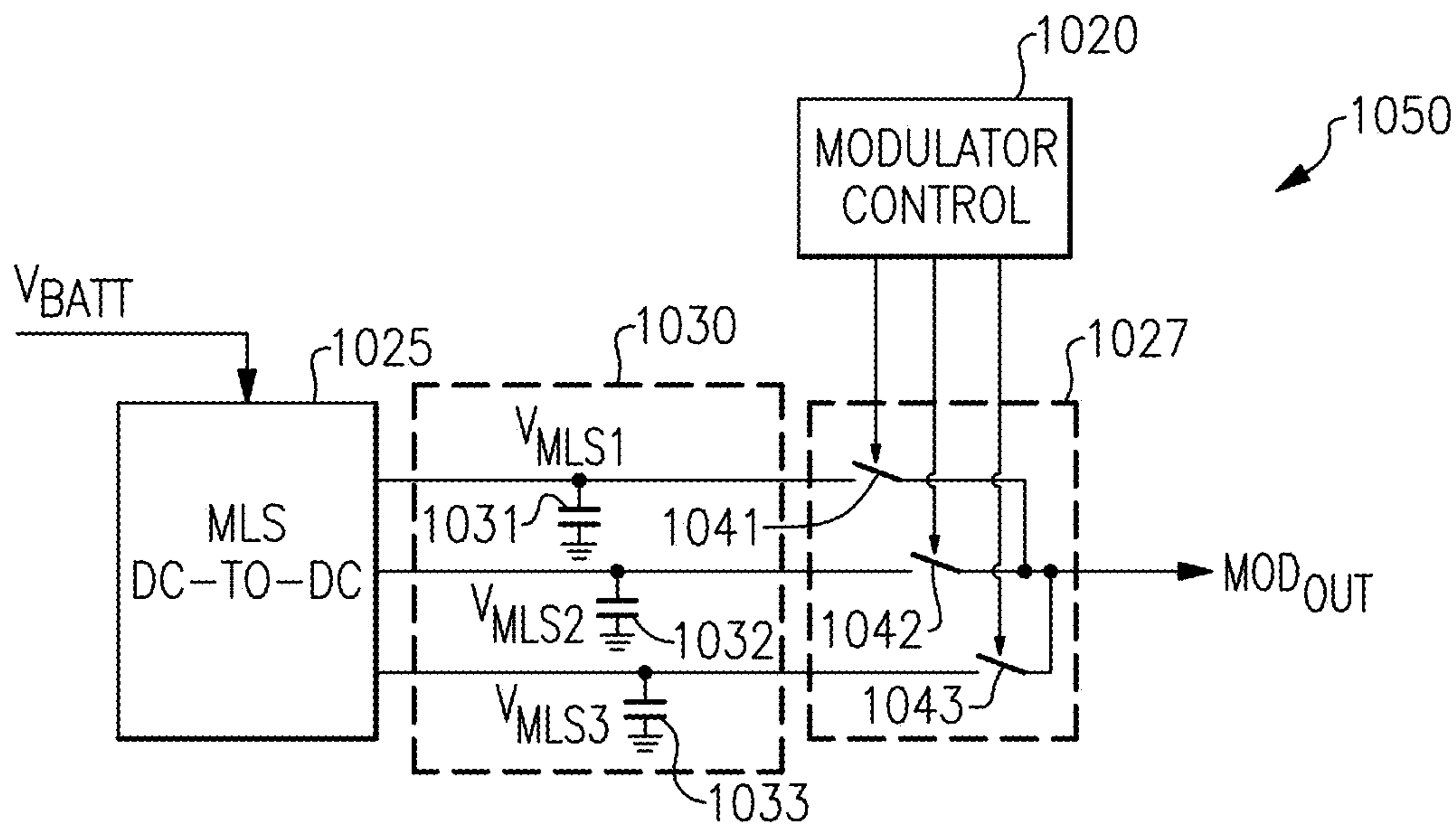
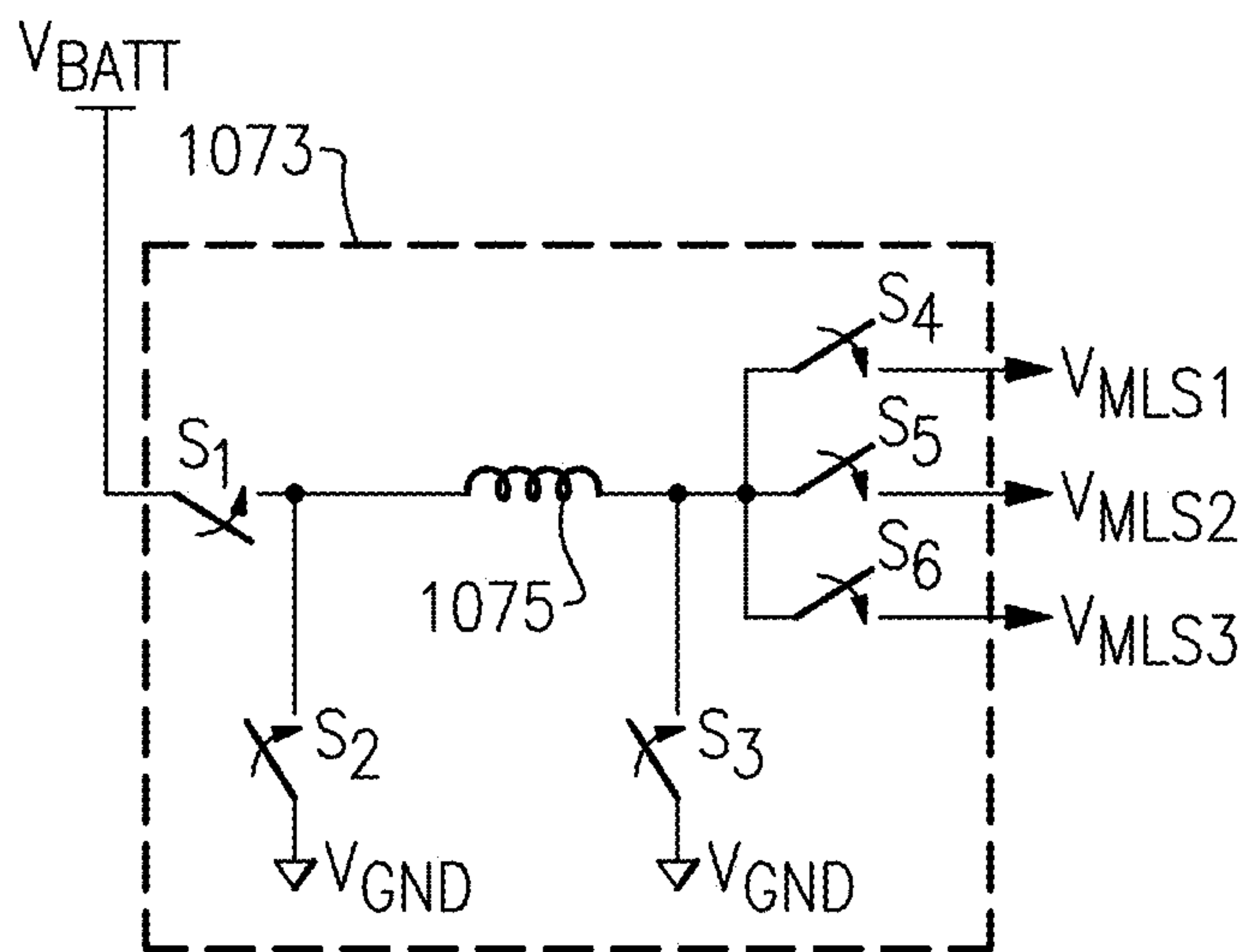


FIG. 8



**FIG.9**



**FIG.10**



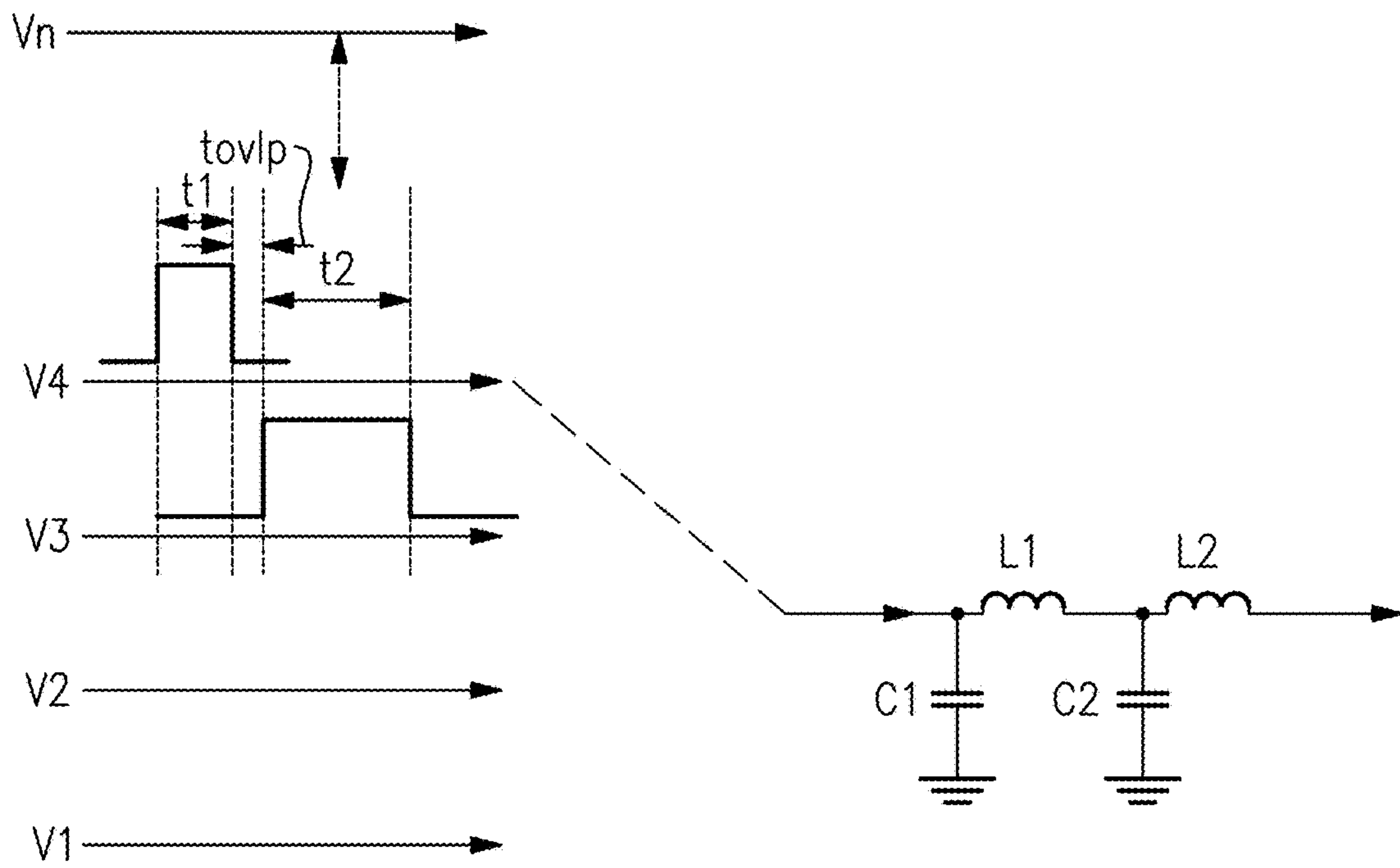


FIG.11

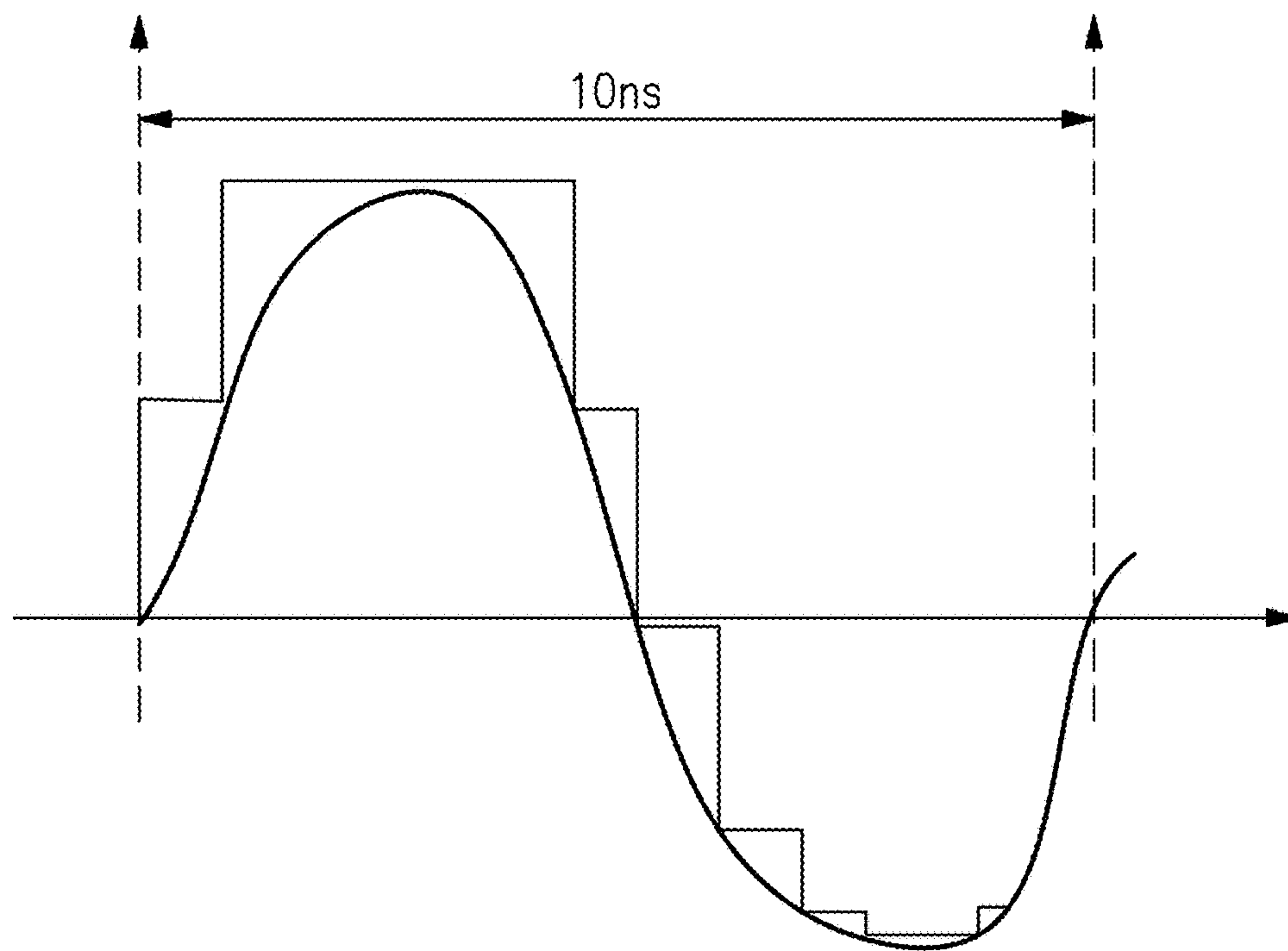
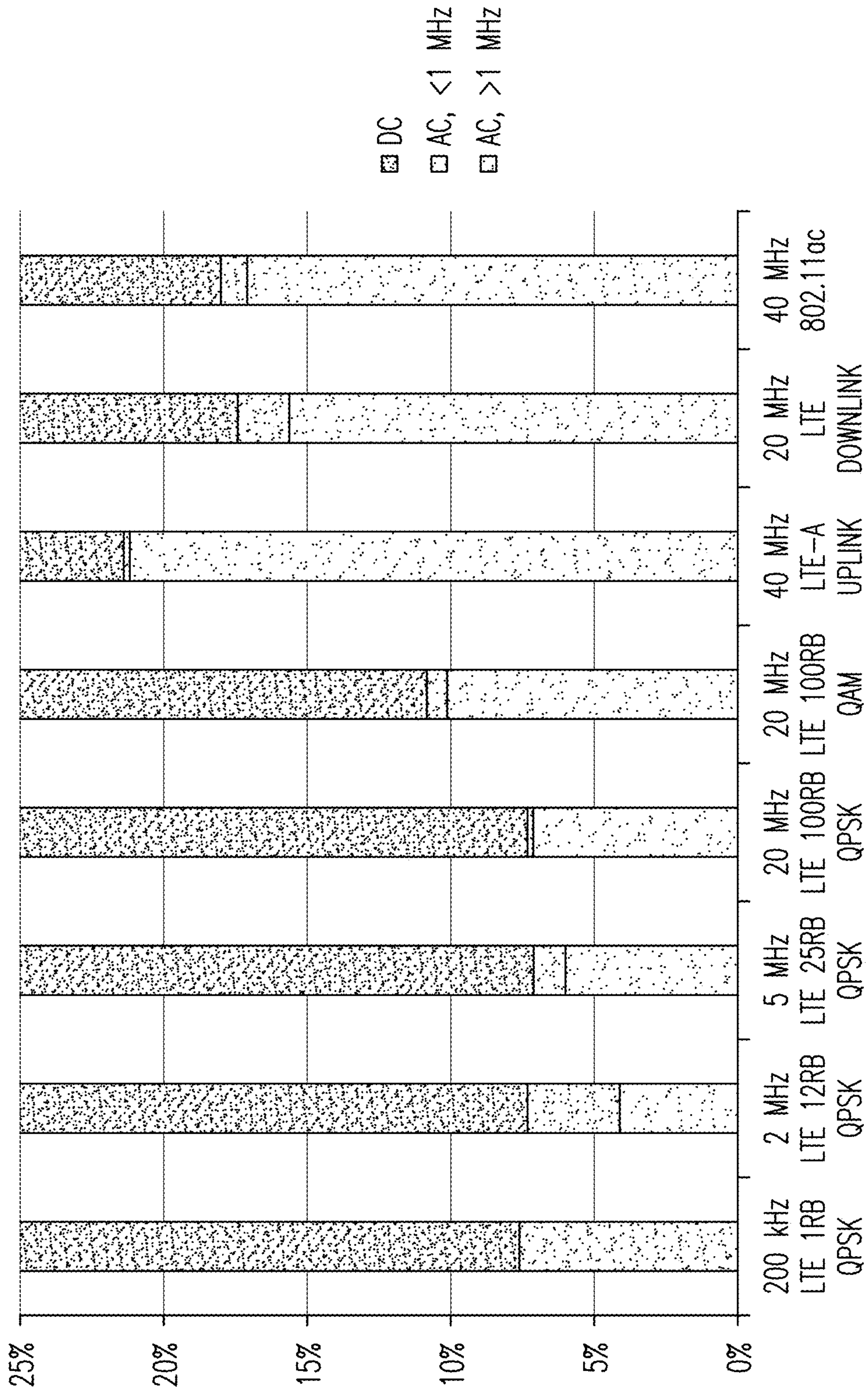


FIG.12



**FIG.13**



**1****MULTI-LEVEL ENVELOPE TRACKING  
SYSTEMS WITH SEPARATE DC AND AC  
PATHS****CROSS-REFERENCE TO RELATED  
APPLICATIONS**

This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Patent Application No. 62/907,120, filed Sep. 27, 2019 and titled "MULTI-LEVEL ENVELOPE TRACKING SYSTEMS WITH SEPARATE DC AND AC PATHS," which is herein incorporated by reference in its entirety.

**BACKGROUND****Field**

Embodiments of the invention relate to electronic systems, and in particular, to power amplifiers for radio frequency (RF) electronics.

**Description of the Related Technology**

Power amplifiers are used in RF communication systems to amplify RF signals for transmission via antennas. It is important to manage the power of RF signal transmissions to prolong battery life and/or provide a suitable transmit power level.

Examples of RF communication systems with one or more power amplifiers include, but are not limited to, mobile phones, tablets, base stations, network access points, customer-premises equipment (CPE), laptops, and wearable electronics. For example, in wireless devices that communicate using a cellular standard, a wireless local area network (WLAN) standard, and/or any other suitable communication standard, a power amplifier can be used for RF signal amplification. An RF signal can have a frequency in the range of about 30 kHz to 300 GHz, such as in the range of about 410 MHz to about 7.125 GHz for fifth generation (5G) communications in frequency range 1 (FR1).

**SUMMARY**

In certain embodiments, the present disclosure relates to an envelope tracking system including a power amplifier configured to amplify a radio frequency signal and to receive power from a power amplifier supply voltage, and an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency signal. The envelope tracker includes a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a second filter coupled between a DC voltage and the power amplifier supply voltage.

In various embodiments, the DC-to-DC converter is further configured to generate the DC voltage. According to a number of embodiments, the DC-to-DC converter is configured to generate the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

In several embodiments, the DC-to-DC converter is configured to receive a battery voltage, and to generate the

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plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage.

In some embodiments, each of the plurality of regulated voltages has a different voltage level.

In various embodiments, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

In several embodiments, the modulator includes a plurality of switches each coupled between the modulator output voltage and a corresponding one of the plurality of regulated voltages.

In some embodiments, the first filter includes at least one series inductor and at least one shunt capacitor. According to a number of embodiments, the first filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

In various embodiments, the second filter includes at least one series inductor and at least one shunt capacitor.

In several embodiments, the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter. According to a number of embodiments, the controllable delay circuit includes a plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

In various embodiments, a DC path through the second filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier.

In certain embodiments, the present disclosure relates to an envelope tracker. The envelope tracker includes a power amplifier supply voltage terminal configured to output a power amplifier supply voltage, a DC-to-DC converter configured to output a plurality of regulated voltages based on regulating a battery voltage, a modulator configured to generate a modulator output voltage based on the plurality of regulated voltages and an envelope signal, an AC path filter coupled between the modulator output voltage and the power amplifier supply voltage, and a DC path filter coupled between a DC voltage and the power amplifier supply voltage.

In several embodiments, the DC-to-DC converter is further configured to generate the DC voltage. According to a number of embodiments, the DC-to-DC converter is configured to generate the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

In some embodiments, the DC-to-DC converter is configured to receive a battery voltage, and to generate the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage.

In various embodiments, each of the plurality of regulated voltages has a different voltage level.

In several embodiments, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

In some embodiments, the modulator includes a plurality of switches each coupled between the modulator output voltage and a corresponding one of the plurality of regulated voltages.

In various embodiments, the AC path filter includes at least one series inductor and at least one shunt capacitor. According to a number of embodiments, the AC path filter



further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

In several embodiments, the DC path filter includes at least one series inductor and at least one shunt capacitor.

In various embodiments, the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter. According to a number of embodiments, the controllable delay circuit includes a plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

In some embodiments, the DC path filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier supply voltage terminal.

In certain embodiments, the present disclosure relates to a mobile device. The mobile device includes a transceiver configured to generate a radio frequency transmit signal, a front end circuit including a power amplifier configured to amplify the radio frequency transmit signal and to receive power from a power amplifier supply voltage, and a power management circuit including an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency transmit signal. The envelope tracker includes a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a second filter coupled between a DC voltage and the power amplifier supply voltage.

In some embodiments, the DC-to-DC converter is further configured to generate the DC voltage. According to a number of embodiments, the DC-to-DC converter is configured to generate the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

In several embodiments, the mobile device further includes a battery that provides a battery voltage, and the DC-to-DC converter is configured to generate the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage.

In some embodiments, each of the plurality of regulated voltages has a different voltage level.

In various embodiments, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

In several embodiments, the modulator includes a plurality of switches each coupled between the modulator output voltage and a corresponding one of the plurality of regulated voltages.

In some embodiments, the first filter includes at least one series inductor and at least one shunt capacitor. According to a number of embodiments, the first filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

In several embodiments, the second filter includes at least one series inductor and at least one shunt capacitor.

In various embodiments, the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter. According to a number of embodiments, the controllable delay circuit includes a

plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

In some embodiments, a DC path through the second filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier.

In certain embodiments, the present disclosure relates to a method of envelope tracking. The method includes amplifying a radio frequency signal using a power amplifier, supplying power to the power amplifier using a power amplifier supply voltage, outputting a plurality of regulated voltages from a DC-to-DC converter, and generating a modulator output voltage based on the plurality of regulated voltages and an envelope signal using a modulator, the envelope signal corresponding to an envelope of the radio frequency signal. The method further includes controlling the power amplifier supply voltage using a first filter that is between the modulator output voltage and the power amplifier supply voltage, and controlling the power amplifier supply voltage using a second filter that is between a DC voltage and the power amplifier supply voltage.

In several embodiments, the method further includes generating the DC voltage using the DC-to-DC converter. According to a number of embodiments, the method further includes generating the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

In various embodiments, the method further includes generating the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of a battery voltage.

In some embodiments, each of the plurality of regulated voltages has a different voltage level.

In several embodiments, the method further includes providing DC blocking using a series DC blocking capacitor of the first filter.

In various embodiments, the method further includes controlling a relative delay between an AC path through the first filter and a DC path through the second filter using a controllable delay circuit.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a mobile device according to one embodiment.

FIG. 2 is a schematic diagram of one embodiment of an envelope tracking system for a power amplifier.

FIG. 3A is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

FIG. 3B is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

FIG. 3C is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

FIG. 3D is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

FIG. 4 is a graph of efficiency versus output power.

FIG. 5 is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

FIG. 6 is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

FIG. 7 is a schematic diagram of a mobile device according to another embodiment.

FIG. 8 is a schematic diagram of one embodiment of a communication system for transmitting radio frequency (RF) signals.

FIG. 9 is a schematic diagram of a multi-level supply (MLS) modulation system according to one embodiment.



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FIG. 10 is a schematic diagram of an MLS DC-to-DC converter according to one embodiment.

FIG. 11 is a schematic diagram of one example of timing for MLS DC-to-DC conversion.

FIG. 12 is a schematic diagram of one example of MLS envelope tracking for a continuous wave signal.

FIG. 13 is a schematic diagram of one example of envelope frequency distribution for various signal waveforms.

## DETAILED DESCRIPTION OF EMBODIMENTS

The following detailed description of certain embodiments presents various descriptions of specific embodiments. However, the innovations described herein can be embodied in a multitude of different ways, for example, as defined and covered by the claims. In this description, reference is made to the drawings where like reference numerals can indicate identical or functionally similar elements. It will be understood that elements illustrated in the figures are not necessarily drawn to scale. Moreover, it will be understood that certain embodiments can include more elements than illustrated in a drawing and/or a subset of the elements illustrated in a drawing. Further, some embodiments can incorporate any suitable combination of features from two or more drawings.

Envelope tracking is a technique that can be used to increase power added efficiency (PAE) of a power amplifier by efficiently controlling a voltage level of a power amplifier supply voltage in relation to an envelope of a radio frequency (RF) signal amplified by the power amplifier. Thus, when the envelope of the RF signal increases, the voltage supplied to the power amplifier can be increased. Likewise, when the envelope of the RF signal decreases, the voltage supplied to the power amplifier can be decreased to reduce power consumption.

A multi-level envelope tracker can include a multi-level supply (MLS) DC-to-DC converter that generates two or more regulated voltages of different voltage levels, an MLS modulator that outputs a selected regulated voltage chosen from the regulated voltages, and a filter that filters the MLS modulator's output to generate a power amplifier supply voltage for a power amplifier.

A multi-level envelope tracker can suffer from degraded efficiency when both DC and AC currents for a power amplifier supply voltage are circulated through switches of the MLS modulator and/or a common filter. For example, power losses are incurred in the DC resistance of the modulator's switches and/or the filter's inductors.

Although the DC resistance of the switches can be implemented to be low (for instance, a small percentage of the power amplifier's DC load), implementing the switches in this manner results in relatively large layout and/or significant switching losses. For instance, when a desired source impedance is about 0.2 Ohm, the switches of the MLS modulator can be constrained to achieve less than 0.2 Ohm of on-state resistance, which can result in a relatively large switch layout.

Multi-level envelope tracking systems with separate DC and AC paths are provided. In certain embodiments, an envelope tracking system for generating a power amplifier supply voltage for a power amplifier is provided. The envelope tracking system includes an MLS DC-to-DC converter that outputs multiple regulated voltages, an MLS modulator that controls selection of the regulated voltages over time based on an envelope signal corresponding to an envelope of the RF signal amplified by the power amplifier,

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an AC path filter coupled between an output of the MLS modulator and the power amplifier supply voltage, and a DC path filter coupled between a DC voltage and the power amplifier supply voltage.

By including a DC path through the DC path filter and a separate AC path through the AC path filter, enhanced efficiency of the envelope tracking system can be achieved. For example, low frequency current, such as DC current, can be provided through the DC path filter (for instance, via a filter inductor), thereby relaxing size and/or DC resistance constraints of the modulator's switches. Accordingly, lower switching losses in the AC path can be achieved, thereby enhancing overall system efficiency. In one example, the DC path carries at least 75% of the energy provided by envelope tracking system to the power amplifier.

Since a fast envelope signal can have an energy content centered about DC, the DC path can provide a high efficiency path for low frequency energy content. Moreover, the DC path filter can include components sizes that are relatively small since the filter's inductors can operate without DC saturation. In one example, the DC path filter is implemented with less than about half the size of the AC path filter. In certain implementations, the AC path filter includes a series DC blocking capacitor to aid in blocking DC current through the AC path filter.

In certain implementations, the DC voltage is a regulated voltage from a DC-to-DC converter. For example, the MLS DC-to-DC converter can also be used to generate the DC voltage. In such implementations, the voltage level of the DC voltage can be the same or different as the voltage level of one of the regulated voltages provided to the MLS modulator.

FIG. 1 is a schematic diagram of a mobile device 70 according to one embodiment. The mobile device 70 includes a primary antenna 1, a diversity antenna 2, a primary antenna tuning circuit 3, a diversity antenna tuning circuit 4, a double-pole double-throw (DPDT) antenna diversity switch 5, a primary front end module 6, a diversity front end module 7, a battery 8, an MLS envelope tracker 9, a transceiver 10, a baseband modem 11, and an application processor 12.

Although one embodiment of a mobile device is shown, the teachings herein are applicable to mobile devices implemented in a wide variety of ways. Accordingly, other implementations are possible.

In the illustrated embodiment, the primary front end module 6 includes a first power amplifier 21, a second power amplifier 22, a third power amplifier 23, a fourth power amplifier 24, a first low noise amplifier 31, a second low noise amplifier 32, a third low noise amplifier 33, a diplexer 42, a transmit/receive band switch 41, a transmit filter 43, a first diplexer 45, a second diplexer 46, a third diplexer 47, a first receive filter 51, a second receive filter 52, a third receive filter 53, a first directional coupler 59, and a second directional coupler 60. Additionally, the diversity front end module 7 includes a first low noise amplifier 35, a second low noise amplifier 36, a first receive filter 55, a second receive filter 56, a first receive band selection switch 61, and a second receive band selection switch 62.

Although one embodiment of front end circuitry is shown, other implementations of front end circuitry are possible. For instance, front end circuitry can include power amplifiers (PAs), low noise amplifiers (LNAs), filters, switches, phase shifters, duplexers, and/or other suitable circuitry for processing RF signals transmitted and/or received from one or more antennas. Example functionalities of a front end include but are not limited to, amplifying signals for trans-



mission, amplifying received signals, filtering signals, switching between different bands, switching between different power modes, switching between transmission and receiving modes, duplexing of signals, multiplexing of signals (for instance, diplexing or triplexing), or some combination thereof.

Accordingly, other implementations of primary front end modules, diversity receive front end modules, antenna selection, and/or antenna tuning can be used.

As shown in FIG. 1, the MLS envelope tracker **9** is used to generate one or more power amplifier supply voltages for power amplifiers used in the mobile device **70** to amplify RF signals for wireless transmission. In the illustrated embodiment, the MLS envelope tracker **9** receives a battery voltage  $V_{BATT}$  from the battery **8**, and generates a first power amplifier supply voltage  $V_{PA1}$  for the first power amplifier **21** and a second power amplifier supply voltage  $V_{PA2}$  for the first power amplifier **22**. Although an example in which the MLS envelope tracker **9** generates two power amplifier supply voltages is shown, the MLS envelope tracker **9** can generate more or fewer power amplifier supply voltages.

The MLS envelope tracker **9** controls the first power amplifier supply voltage  $V_{PA1}$  to track an envelope of a first RF signal amplified by the first power amplifier **21**. Additionally, the MLS envelope tracker **9** controls the second power amplifier supply voltage  $V_{PA2}$  to track an envelope of a second RF signal amplified by the second power amplifier **22**. In certain implementations, the MLS envelope tracker **9** receives one or more envelope signals from the baseband modem **11**. For example, the MLS envelope tracker **9** can receive a first envelope signal indicating an envelope of the first RF signal and a second envelope signal indicating an envelope of the second RF signal.

The battery **8** can be any suitable battery for use in the mobile device **70**, including, for example, a lithium-ion battery. The battery voltage  $V_{BATT}$  is regulated by a DC-to-DC converter of the MLS envelope tracker **9** to generate regulated voltages used for multi-level envelope tracking in accordance with the teachings herein.

The transceiver **10** generates RF signals for transmission and processes incoming RF signals received from the primary antenna **1** and the diversity antenna **2**. It will be understood that various functionalities associated with the transmission and receiving of RF signals can be achieved by one or more components that are collectively represented in FIG. 1 as the transceiver **10**. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

The baseband modem **11** provides the transceiver **10** with digital representations of transmit signals, which the transceiver **10** processes to generate RF signals for transmission. The baseband modem **11** also processes digital representations of received signals provided by the transceiver **10**.

As shown in FIG. 1, the baseband modem **11** is coupled to the application processor **12**, which serves to provide primary application processing in the mobile device **70**. The application processor **12** can provide a wide variety of functions, such as providing system capabilities suitable for supporting applications, including, but not limited to, memory management, graphics processing, and/or multimedia decoding.

Although the mobile device **70** illustrates one example of an RF system including a multi-level envelope tracker, a wide variety of RF systems can include a multi-level envelope tracker implemented in accordance with the teachings herein.

FIGS. 2-3C, **5** and **6** depict schematic diagram of various embodiments of envelope tracking systems for a power amplifier. However, the teachings herein are applicable to envelope trackers implemented in a wide variety of ways. Accordingly, other implementations are possible.

FIG. 2 is a schematic diagram of one embodiment of an envelope tracking system **100** for a power amplifier **71**. The envelope tracking system **100** includes an MLS DC-to-DC converter **72**, a DC path filter **73**, an MLS modulator **81**, and an AC path filter **91**. The MLS DC-to-DC converter **72** is also referred to herein as a switching regulator.

The power amplifier **71** amplifies an RF input signal  $RF_{IN}$  to generate an RF output signal  $RF_{OUT}$ . The MLS modulator **81** receives an envelope signal (ENVELOPE), which changes in relation to an envelope of the RF input signal  $RF_{IN}$ . The envelope signal can be analog or digital.

In the illustrated embodiment, the MLS DC-to-DC converter **72** receives a battery voltage  $V_{BATT}$ , and provides DC-to-DC conversion to generate a variety of regulated voltages  $V_{MLSa}$ ,  $V_{MLSb}$ ,  $V_{MLSc}$ , . . .  $V_{MLSn}$  of different voltage levels. Although an example in which four MLS voltages is depicted, the MLS DC-to-DC converter **72** can generate more or fewer MLS voltages as indicated by the ellipses. In this embodiment, the MLS DC-to-DC converter **72** also generates the DC voltage  $V_{DC}$  by regulating the battery voltage  $V_{BATT}$ . The DC voltage  $V_{DC}$  can be of the same or different voltage level as one of the regulated voltages  $V_{MLSa}$ ,  $V_{MLSb}$ ,  $V_{MLSc}$ , . . .  $V_{MLSn}$ .

The MLS modulator **81** receives the regulated voltages  $V_{MLSa}$ ,  $V_{MLSb}$ ,  $V_{MLSc}$ , . . .  $V_{MLSn}$  and the envelope signal, and outputs a modulator output voltage to the AC path filter **91**. In certain implementations, the MLS modulator **81** controls the outputted voltage based on selecting a suitable regulated voltage over time based on the envelope signal. For example, the MLS modulator **81** can include a bank of switches for selectively connecting the regulated voltages  $V_{MLSa}$ ,  $V_{MLSb}$ ,  $V_{MLSc}$ , . . .  $V_{MLSn}$  to the modulator's output based on a value of the envelope signal.

The DC path filter **73** and the AC path filter **91** filter the DC voltage  $V_{DC}$  from the MLS DC-to-DC converter **72** and the output of MLS modulator **81**, respectively, to thereby generate a power amplifier supply voltage  $V_{PA}$  for the power amplifier **71**.

By including a DC path through the DC path filter **73** and a separate AC path through the AC path filter **91**, enhanced efficiency of the envelope tracking system **100** can be achieved. For example, low frequency current (including, but not limited to, DC current) can be provided through the DC path filter **73**, thereby relaxing size and/or DC resistance constraints of the MLS modulator's switches.

Accordingly, lower switching losses in the AC path can be achieved, thereby enhancing overall system efficiency. In one example, the DC path carries at least 75% of the energy provided by envelope tracking system **100** to the power amplifier **71**.

FIG. 3A is a schematic diagram of another embodiment of an envelope tracking system **140** for a power amplifier **101**. The envelope tracking system **140** includes an envelope tracking integrated circuit (IC) **102**, a DC path filter **103**, an AC path filter **104**, DAC circuitry **105**, an envelope filter **106**, first to fourth decoupling capacitors **111-114**, respectively, and an inductor **117**.

Although one embodiment of an envelope tracking system is shown in FIG. 3A, the teachings herein are applicable to envelope tracking systems implemented in a wide variety of ways. Accordingly, other implementations are possible.



In the illustrated embodiment, the envelope tracking IC **102** includes MLS switching circuitry **121**, a digital control circuit **122**, a baseband MLS modulator **123**, and a modulator control circuit **124**. The envelope tracking IC **102** of FIG. **3A** is depicted with various pins or pads for providing a variety of functions, such as receiving a battery voltage ( $V_{BATT}$ ), communicating over a serial peripheral interface (SPI), outputting a DC voltage  $V_{DC}$ , receiving an envelope signal (ENVELOPE), connecting to the decoupling capacitors **111-114**, and connecting to the inductor **117**. An envelope tracking IC is also referred to herein in as an envelope tracking semiconductor die or chip.

The MLS switching circuitry **121** controls a current through the inductor **117** to provide voltage regulation. For example, the MLS switching circuitry **121** can include switches and a controller that turns on and off the switches using any suitable regulation scheme (including, but not limited to, pulse-width modulation) to provide DC-to-DC conversion. In the illustrated embodiment, the MLS switching circuitry **121** outputs four regulated MLS voltages of different voltage levels and a regulated DC voltage  $V_{DC}$ . However, the MLS switching circuitry **121** can be implemented to output more or fewer regulated voltages.

As shown in FIG. **3A**, the MLS switching circuitry **121** is controlled by the digital control circuit **122**. The digital control circuit **122** can provide programmability to the MLS switching circuitry **121** including, but not limited to, control over voltage levels of one or more regulated voltages outputted by the MLS switching circuitry **121**. As shown in FIG. **3A**, the digital control circuit **122** is coupled to the SPI bus. In certain implementations, the digital control circuit **122** controls the MLS switching circuitry **121** based on data received over the SPI bus and/or other chip interface.

The MLS switching circuitry **121** can also be controlled by the modulator control circuit **124**. In one example, the regulated DC voltage  $V_{DC}$  is controlled at least in part by the modulator control circuit **124**.

The baseband MLS modulator **123** includes an output coupled to the power amplifier supply voltage  $V_{PA}$  through the AC path filter **104**. In certain implementations, the baseband MLS modulator **123** includes switches coupled between each of the regulated MLS voltages and the AC path filter **104**. Additionally, the modulator's switches are selectively opened or closed by the modulator controller **124** based on the envelope signal.

In the illustrated embodiment, the DC path filter **103** includes a shunt capacitor **127** and a series inductor **128**. Additionally, the AC path filter **104** includes a first series inductor **131**, a second series inductor **132**, a first shunt capacitor **135**, and a second shunt capacitor **136**. Although example implementations of a DC path filter and an AC path filter are depicted in FIG. **3A**, the teachings herein are applicable to DC path filters and AC path filters implemented in a wide variety of ways. Accordingly, other implementations of filters can be used in accordance with the teachings herein.

In certain implementations, one or more components of a filter are controllable (for instance, digitally programmable and/or analog-tuned) to provide enhanced flexibility and/or configurability. For example, in the illustrated embodiment, the first shunt capacitor **135** and the second shunt capacitor **136** are controllable. Although two examples of controllable filter components are shown, other filter components can additionally or alternatively be implemented to be controllable.

FIG. **3B** is a schematic diagram of another embodiment of an envelope tracking system **150** for a power amplifier **101**.

The envelope tracking system **150** of FIG. **3B** is similar to the envelope tracking system **140** of FIG. **3A**, except that the envelope tracking system **150** includes a different implementation of an AC path filter **144**.

For example, in comparison to the AC path filter **104** of FIG. **3A**, the AC path filter **144** of FIG. **3B** further includes a DC blocking capacitor **138** for blocking low frequency current through the AC path filter **144**. In the illustrated embodiment, the DC blocking capacitor **138** is coupled to the output of the AC path filter **144**.

By including the DC blocking capacitor **138**, lower switching losses in the AC path can be achieved, thereby enhancing overall system efficiency. For example, inclusion of the DC blocking capacitor **138** can aid in increasing a percentage of energy carried by the DC path through the DC path filter **103** relative to the energy carried by the AC path through the AC path filter **144**. In one example, the DC path through the DC path filter **103** carries at least 75% of the energy provided by envelope tracking system **150** to the power amplifier **101**.

FIG. **3C** is a schematic diagram of another embodiment of an envelope tracking system **160** for a power amplifier **101**. The envelope tracking system **160** of FIG. **3C** is similar to the envelope tracking system **150** of FIG. **3B**, except that the envelope tracking system **160** includes a different implementation of an AC path filter **154**.

For example, in comparison to the AC path filter **144** of FIG. **3B**, the AC path filter **154** of FIG. **3C** includes the DC blocking capacitor **138** coupled to the filter's input. A DC blocking capacitor can be included in an AC path filter in a wide variety of locations, including, for example, at the input, at the output, or along the signal path between the input and the output.

FIG. **3D** is a schematic diagram of another embodiment of an envelope tracking system **170** for a power amplifier **101**. The envelope tracking system **170** of FIG. **3D** is similar to the envelope tracking system **140** of FIG. **3A**, except that the envelope tracking system **170** includes an envelope tracking IC **102** operating with two MLS regulated voltages. Additionally the decoupling capacitors **113** and **114** have been omitted in view of the fewer number of MLS regulated voltages.

The envelope tracking system **170** of FIG. **3D** has the advantage of lower complexity. Moreover, the envelope tracking system **170** is well-suited for applications using symbol by symbol tracking, which can be suitable for high bandwidth modulations. For example, when using symbol by symbol tracking, two MLS voltages can be programmed and used in succession at the symbol rate (for instance, 16 us). Thus, the MLS modulator **123** can change the voltage used for generating the power amplifier supply voltage by switching to the new voltage holding capacitor.

When using symbol by symbol tracking, less filtering can be used, but the AC/DC split is nevertheless beneficial and avoids a need for a series switch.

FIG. **4** is a graph of efficiency versus output power. The graph includes three plots of combined power amplifier and envelope tracker efficiency versus output power for different simulation scenarios. For example, the first plot **171** corresponds to a simulation in which 0.1 Ohm of switch resistance is included in the DC path, a second plot **172** of LTE efficiency, and a third plot **173** in which 1.0 Ohm of switch resistance is included in the DC path. Since lower DC path resistance can be achieved by providing a separate AC path and DC path, enhanced efficiency can also be realized.

Although specific examples of simulation results for envelope tracking systems are shown in FIG. **4**, other



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simulations results are possible. For example, simulation results can vary based on a wide variety of factors, including, but not limited to, simulation parameters (including operating frequency), circuit topology, and/or fabrication processes.

FIG. 5 is a schematic diagram of another embodiment of an envelope tracking system **180** for a power amplifier **71**. The envelope tracking system **180** of FIG. 5 is similar to the envelope tracking system **100** of FIG. 2, except that the envelope tracking system **150** further includes a controllable delay circuit **98**.

In the illustrated embodiment, the envelope tracking system **180** operates with a DC path delay  $t_1$  from the MLS DC-to-DC converter **72** to a supply input of the power amplifier **71** through the DC path filter **73**. Additionally, the envelope tracking system **180** operates with an AC path delay  $t_2$  from the MLS DC-to-DC converter **72** to the supply input of the power amplifier **71** through the controllable delay circuit **98**, the MLS modulator **81**, and the AC path filter **91**.

By including the controllable delay circuit **98**, a relative delay between the AC path and the DC path can be controlled to enhance the efficiency of the envelope tracking system **180**. In certain implementations, a delay of the controllable delay circuit **98** operates to substantially match the DC path delay  $t_1$  and the AC path delay  $t_2$  with a desired phase shift to enhance efficiency.

For example, absent compensation for the difference in delay, currents of the AC path and DC path can fight due to the control bandwidth of the DC path being smaller than the control bandwidth of the AC path. In this example, the AC path is delayed by the controllable delay circuit **98** to control a relative delay of the DC path as seen by the load. In certain implementations, a phase shift of about 90 degrees across the bandwidth where combining occurs provides relatively high efficiency. In certain implementations, a digital state machine or other suitable control circuit operates to provide control that achieves about 90 degrees of phase delay.

FIG. 6 is a schematic diagram of another embodiment of an envelope tracking system **200** for a power amplifier **101**. The envelope tracking system **200** of FIG. 6 is similar to the envelope tracking system **140** of FIG. 3A, except that the envelope tracking system **200** includes a different implementation of an envelope tracking IC **182**.

For example, in comparison to the envelope tracking IC **102** of FIG. 3A, the envelope tracking IC **182** of FIG. 6 further includes controllable delay buffers **191-194**. As shown in FIG. 3A, the controllable delay buffers **191-194** provide controllable delay to each MLS regulated voltage generated by the MLS switching circuit **121**, thereby allowing for relatively adjustment of the AC path delay  $t_2$  relative to the DC path delay  $t_1$ .

In this embodiment, the delay of the controllable delay buffers **191-194** are separately controllable by the digital control circuit **122**, thereby providing enhanced flexibility in accounting for any variations in delay between the various MLS regulated voltage paths.

FIG. 7 is a schematic diagram of a mobile device **800** according to another embodiment. The mobile device **800** includes a baseband system **801**, a transceiver **802**, a front end system **803**, antennas **804**, a power management system **805**, a memory **806**, a user interface **807**, and a battery **808**.

The mobile device **800** can be used communicate using a wide variety of communications technologies, including, but not limited to, 2G, 3G, 4G (including LTE, LTE-Advanced, and LTE-Advanced Pro), 5G, WLAN (for instance, Wi-Fi),

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WPAN (for instance, Bluetooth and ZigBee), WMAN (for instance, WiMax), and/or GPS technologies.

The transceiver **802** generates RF signals for transmission and processes incoming RF signals received from the antennas **804**. It will be understood that various functionalities associated with the transmission and receiving of RF signals can be achieved by one or more components that are collectively represented in FIG. 7 as the transceiver **802**. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

The front end system **803** aids is conditioning signals transmitted to and/or received from the antennas **804**. In the illustrated embodiment, the front end system **803** includes power amplifiers (PAs) **811**, low noise amplifiers (LNAs) **812**, filters **813**, switches **814**, and duplexers **815**. However, other implementations are possible.

For example, the front end system **803** can provide a number of functionalizes, including, but not limited to, amplifying signals for transmission, amplifying received signals, filtering signals, switching between different bands, switching between different power modes, switching between transmission and receiving modes, duplexing of signals, multiplexing of signals (for instance, duplexing or triplexing), or some combination thereof.

In certain implementations, the mobile device **800** supports carrier aggregation, thereby providing flexibility to increase peak data rates. Carrier aggregation can be used for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), and may be used to aggregate a plurality of carriers or channels. Carrier aggregation includes contiguous aggregation, in which contiguous carriers within the same operating frequency band are aggregated. Carrier aggregation can also be non-contiguous, and can include carriers separated in frequency within a common band or in different bands.

The antennas **804** can include antennas used for a wide variety of types of communications. For example, the antennas **804** can include antennas associated transmitting and/or receiving signals associated with a wide variety of frequencies and communications standards.

In certain implementations, the antennas **804** support MIMO communications and/or switched diversity communications. For example, MIMO communications use multiple antennas for communicating multiple data streams over a single radio frequency channel. MIMO communications benefit from higher signal to noise ratio, improved coding, and/or reduced signal interference due to spatial multiplexing differences of the radio environment. Switched diversity refers to communications in which a particular antenna is selected for operation at a particular time. For example, a switch can be used to select a particular antenna from a group of antennas based on a variety of factors, such as an observed bit error rate and/or a signal strength indicator.

The mobile device **800** can operate with beamforming in certain implementations. For example, the front end system **803** can include phase shifters having variable phase controlled by the transceiver **802**. Additionally, the phase shifters are controlled to provide beam formation and directivity for transmission and/or reception of signals using the antennas **804**. For example, in the context of signal transmission, the phases of the transmit signals provided to the antennas **804** are controlled such that radiated signals from the antennas **804** combine using constructive and destructive interference to generate an aggregate transmit signal exhibiting beam-like qualities with more signal strength propagating in a given direction. In the context of signal reception,



the phases are controlled such that more signal energy is received when the signal is arriving to the antennas **804** from a particular direction. In certain implementations, the antennas **804** include one or more arrays of antenna elements to enhance beamforming.

The baseband system **801** is coupled to the user interface **807** to facilitate processing of various user input and output (I/O), such as voice and data. The baseband system **801** provides the transceiver **802** with digital representations of transmit signals, which the transceiver **802** processes to generate RF signals for transmission. The baseband system **801** also processes digital representations of received signals provided by the transceiver **802**. As shown in FIG. 7, the baseband system **801** is coupled to the memory **806** of facilitate operation of the mobile device **800**.

The memory **806** can be used for a wide variety of purposes, such as storing data and/or instructions to facilitate the operation of the mobile device **800** and/or to provide storage of user information.

The power management system **805** provides a number of power management functions of the mobile device **800**. The power management system **805** can include an MLS envelope tracker **860** implemented in accordance with one or more features of the present disclosure.

As shown in FIG. 7, the power management system **805** receives a battery voltage form the battery **808**. The battery **808** can be any suitable battery for use in the mobile device **800**, including, for example, a lithium-ion battery.

FIG. 8 is a schematic diagram of one embodiment of a communication system **950** for transmitting RF signals. The communication system **950** includes a battery **901**, an MLS envelope tracker **902**, a power amplifier **903**, a directional coupler **904**, a duplexing and switching circuit **905**, an antenna **906**, a baseband processor **907**, a signal delay circuit **908**, a digital pre-distortion (DPD) circuit **909**, an I/Q modulator **910**, an observation receiver **911**, an intermodulation detection circuit **912**, an envelope delay circuit **921**, a coordinate rotation digital computation (CORDIC) circuit **922**, a shaping circuit **923**, a digital-to-analog converter **924**, and a reconstruction filter **925**.

The communication system **950** of FIG. 8 illustrates one example of an RF system that can include an envelope tracking system implemented in accordance with one or more features of the present disclosure. However, the teachings herein are applicable to RF systems implemented in a wide variety of ways.

The baseband processor **907** operates to generate an in-phase (I) signal and a quadrature-phase (Q) signal, which correspond to signal components of a sinusoidal wave or signal of a desired amplitude, frequency, and phase. For example, the I signal and the Q signal provide an equivalent representation of the sinusoidal wave. In certain implementations, the I and Q signals are outputted in a digital format. The baseband processor **907** can be any suitable processor for processing baseband signals. For instance, the baseband processor **907** can include a digital signal processor, a microprocessor, a programmable core, or any combination thereof.

The signal delay circuit **908** provides adjustable delay to the I and Q signals to aid in controlling relative alignment between the differential envelope signal ENV\_p, ENV\_n provided to the MLS envelope tracker **902** and the RF signal RF<sub>IN</sub> provided to the power amplifier **903**. The amount of delay provided by the signal delay circuit **908** is controlled based on amount of intermodulation in adjacent bands detected by the intermodulation detection circuit **912**.

The DPD circuit **909** operates to provide digital shaping to the delayed I and Q signals from the signal delay circuit **908** to generate digitally pre-distorted I and Q signals. In the illustrated embodiment, the DPD provided by the DPD circuit **909** is controlled based on amount of intermodulation detected by the intermodulation detection circuit **912**. The DPD circuit **909** serves to reduce a distortion of the power amplifier **903** and/or to increase the efficiency of the power amplifier **903**.

The I/Q modulator **910** receives the digitally pre-distorted I and Q signals, which are processed to generate the RF signal RF<sub>IN</sub>. For example, the I/Q modulator **910** can include DACs configured to convert the digitally pre-distorted I and Q signals into an analog format, mixers for upconverting the analog I and Q signals to radio frequency, and a signal combiner for combining the upconverted I and Q signals into the RF signal RF<sub>IN</sub>. In certain implementations, the I/Q modulator **910** can include one or more filters configured to filter frequency content of signals processed therein.

The envelope delay circuit **921** delays the I and Q signals from the baseband processor **907**. Additionally, the CORDIC circuit **922** processes the delayed I and Q signals to generate a digital envelope signal representing an envelope of the RF signal RF<sub>IN</sub>. Although FIG. 8 illustrates an implementation using the CORDIC circuit **922**, an envelope signal can be obtained in other ways.

The shaping circuit **923** operates to shape the digital envelope signal to enhance the performance of the communication system **950**. In certain implementations, the shaping circuit **923** includes a shaping table that maps each level of the digital envelope signal to a corresponding shaped envelope signal level. Envelope shaping can aid in controlling linearity, distortion, and/or efficiency of the power amplifier **903**.

In the illustrated embodiment, the shaped envelope signal is a digital signal that is converted by the DAC **924** to a differential analog envelope signal. Additionally, the differential analog envelope signal is filtered by the reconstruction filter **925** to generate a differential envelope signal ENV\_p, ENV\_n suitable for use by a differential envelope amplifier of the MLS envelope tracker **902**. In certain implementations, the reconstruction filter **925** includes a differential low pass filter.

Although one example of envelope signaling is shown, the teachings herein are applicable to envelope signaling implemented in a wide variety of ways. For instance, in another example, the DAC **924** and the reconstruction filter **925** are omitted in favor of providing the MLS envelope tracker **902** with digital envelope data.

With continuing reference to FIG. 8, the MLS envelope tracker **902** receives the envelope signal from the reconstruction filter **925** and a battery voltage V<sub>BATT</sub> from the battery **901**, and uses the differential envelope signal ENV\_p, ENV\_n to generate a power amplifier supply voltage V<sub>CC\_PA</sub> for the power amplifier **903** that changes in relation to the envelope of the RF signal RF<sub>IN</sub>. The power amplifier **903** receives the RF signal RF<sub>IN</sub> from the I/Q modulator **910**, and provides an amplified RF signal RF<sub>OUT</sub> to the antenna **906** through the duplexing and switching circuit **905**, in this example.

The directional coupler **904** is positioned between the output of the power amplifier **903** and the input of the duplexing and switching circuit **905**, thereby allowing a measurement of output power of the power amplifier **903** that does not include insertion loss of the duplexing and switching circuit **905**. The sensed output signal from the directional coupler **904** is provided to the observation



receiver **911**, which can include mixers for providing down conversion to generate downconverted I and Q signals, and DACs for generating I and Q observation signals from the downconverted I and Q signals.

The intermodulation detection circuit **912** determines an intermodulation product between the I and Q observation signals and the I and Q signals from the baseband processor **907**. Additionally, the intermodulation detection circuit **912** controls the DPD provided by the DPD circuit **909** and/or a delay of the signal delay circuit **908** to control relative alignment between the differential envelope signal  $ENV_p$ ,  $ENV_n$  and the RF signal  $RF_{IN}$ . In another embodiment, the intermodulation detection circuit **912** additionally or alternatively controls a delay of the signal delay circuit **921**.

By including a feedback path from the output of the power amplifier **903** and baseband, the I and Q signals can be dynamically adjusted to optimize the operation of the communication system **950**. For example, configuring the communication system **950** in this manner can aid in providing power control, compensating for transmitter impairments, and/or in performing DPD.

Although illustrated as a single stage, the power amplifier **903** can include one or more stages. Furthermore, the teachings herein are applicable to communication systems including multiple power amplifiers.

FIG. **9** is a schematic diagram of an MLS modulation system **1050** according to one embodiment. The MLS modulation system **1050** includes a modulator control circuit **1020**, an MLS DC-to-DC converter **1025**, a modulator switch bank **1027**, and a decoupling capacitor bank **1030**.

The MLS modulation system **1050** of FIG. **9** illustrates one implementation of MLS modulator circuitry suitable for incorporation in a multi-level envelope tracker. However, other implementations of MLS modulator circuitry can be included in multi-level envelope trackers implemented in accordance with the teachings herein.

The MLS DC-to-DC converter **1025** generates a first regulated voltage  $V_{MLS1}$ , a second regulated voltage  $V_{MLS2}$ , and a third regulated voltage  $V_{MLS3}$  based on providing DC-to-DC conversion of a battery voltage  $V_{BATT}$ . Although an example with three regulated voltages is shown, the MLS DC-to-DC converter **1025** can generate more or fewer regulated voltages. In certain implementations, at least a portion of the regulated voltages are boosted relative to the battery voltage  $V_{BATT}$ . Additionally or alternatively, one or more of the regulated voltages is a buck voltage having a voltage lower than the battery voltage  $V_{BATT}$ .

The decoupling capacitor bank **1030** aids in stabilizing the regulated voltages generated by the MLS DC-to-DC converter **1025**. For example, the decoupling capacitor bank **1030** of FIG. **9** includes a first decoupling capacitor **1031** for decoupling the first regulated voltage  $V_{MLS1}$ , a second decoupling capacitor **1032** for decoupling the second regulated voltage  $V_{MLS2}$ , and a third decoupling capacitor **1033** for decoupling the third regulated voltage  $V_{MLS3}$ .

With continuing reference to FIG. **9**, the modulator switch bank **1027** includes a first switch **1041** connected between the modulator's output ( $MOD_{OUT}$ ) and the first regulated voltage  $V_{MLS1}$ , a second switch **1042** connected between the modulator's output and the second regulated voltage  $V_{MLS2}$ , and a third switch **1043** connected between the modulator's output and the third regulated voltage  $V_{MLS3}$ . The modulator control **1020** operates to selectively open or close the switches **1041-1043** to thereby control modulator's output.

FIG. **10** is a schematic diagram of an MLS DC-to-DC converter **1073** according to one embodiment. The MLS DC-to-DC converter **1073** includes an inductor **1075**, a first

switch  $S_1$ , a second switch  $S_2$ , a third switch  $S_3$ , a fourth switch  $S_4$ , a fifth switch  $S_5$ , and a sixth switch  $S_6$ . The MLS DC-to-DC converter **1073** further includes control circuitry (not shown in FIG. **10**) for opening and closing the switches to provide regulation.

The MLS DC-to-DC converter **1073** of FIG. **10** illustrates one implementation of an MLS DC-to-DC converter suitable for incorporation in a multi-level envelope tracker. However, other implementations of MLS DC-to-DC converters can be included in multi-level envelope trackers implemented in accordance with the teachings herein.

In the illustrated embodiment, the first switch  $S_1$  includes a first end electrically connected to the battery voltage  $V_{BATT}$  and a second end electrically connected to a first end of the second switch  $S_2$  and to a first end of the inductor **1075**. The second switch  $S_2$  further includes a second end electrically connected to a first or ground supply  $V_{GND}$ . Although FIG. **10** illustrates a configuration of a DC-to-DC converter that is powered using a ground supply and a battery voltage, the teachings herein are applicable to DC-to-DC converters powered using any suitable power supplies. The inductor **1075** further includes a second end electrically connected to a first end of each of the third to sixth switches  $S_3$ - $S_6$ . The third switch  $S_3$  further includes a second end electrically connected to the ground supply  $V_{GND}$ . The fourth, fifth, and sixth switches  $S_4$ - $S_6$  each include a second end configured to generate the first, second, and third regulated voltages  $V_{MLS1}$ ,  $V_{MLS2}$ , and  $V_{MLS3}$ , respectively.

The first to sixth switches  $S_1$ - $S_6$  are selectively opened or closed to maintain regulated voltages within a particular error tolerance of target voltage levels. Although an example with three regulated voltages is shown, the MLS DC-to-DC converter **1073** can be implemented to generate more or fewer regulated voltages.

In the illustrated embodiment, the MLS DC-to-DC converter **1073** operates as a buck-boost converter operable to generate regulated boost voltages greater than the battery voltage  $V_{BATT}$  and/or regulated buck voltages lower than the battery voltage  $V_{BATT}$ . However, other implementations are possible.

FIG. **11** is a schematic diagram of one example of timing for MLS DC-to-DC conversion. As shown in FIG. **11**, the width of regulation cycles can be used to control the voltage level of the regulated voltages generated by MLS DC-to-DC conversion. For instance, one MLS regulated voltage can be associated with a period  $t_1$ , while a second regulation voltage can be associated with a different period  $t_2$ . Additionally, a non-overlap period  $t_{ovlp}$  can be used to avoid crowbar currents between different voltage levels.

In certain implementations herein, one or more regulation periods (for instance,  $t_1$  and/or  $t_2$ ) and/or one or more non-overlap period (for instance,  $t_{ovlp}$ ) are digitally controllable. In certain implementations, the delays are controlled based on a digital state machine and/or other suitable circuitry.

The regulated voltages generated by MLS DC-to-DC conversion can be selectively provided by a modulator to a modulator output filter. In the illustrated example, the modulator output filter is depicted as including shunt capacitors **C1** and **C2** and series inductors **L1** and **L2**. However, other implementations of modulator output filters are possible.

Providing both an AC path through a modulator output filter and a separate DC path that bypasses the modulator provides enhanced efficiency. For instance, by implementing the envelope tracking system in this manner, the energy accumulated in the inductors of the modulator's output filter (for instance, inductors **L1** and/or **L2**) can be reduced. This



reduced energy in turn decreases overshoot into the filter and/or back-crowbar current into the MLS switches.

In one embodiment, an MLS DC-to-DC converter generates two or more MLS voltages for a modulator that controls a power amplifier supply voltage, and a DC voltage that controls the power amplifier supply voltage through a DC path that bypasses the modulator. Additionally, the regulation of the DC voltage is different from the regulation of the MLS voltages. For example, the regulation period and/or non-overlap period used for regulation can be different for the DC voltage relative to the MLS voltages. Thus, pulse-width modulator (PWM) sequence can be different for the DC path versus the AC path.

FIG. 12 is a schematic diagram of one example of MLS envelope tracking for a continuous wave signal. The example shown is for a continuous wave signal having a frequency of about 100 MHz and a corresponding period of about 10 ns. Examples of suitable MLS voltage levels for the signal are shown.

FIG. 13 is a schematic diagram of one example of envelope frequency distribution for various signal waveforms. For each type of signal waveform, the graph depicts the percentage of DC envelope energy, AC envelope energy less than 1 MHz, and AC envelope energy greater than 1 MHz. Providing both an AC path through a modulator output filter and a separate DC path that bypasses the modulator provides enhanced efficiency for a variety of types of RF signal waveforms.

## CONCLUSION

Some of the embodiments described above have provided examples in connection with mobile devices. However, the principles and advantages of the embodiments can be used for any other systems or apparatus that have needs for envelope tracking.

Unless the context clearly requires otherwise, throughout the description and the claims, the words “comprise,” “comprising,” and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of “including, but not limited to.” The word “coupled”, as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Likewise, the word “connected”, as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the words “herein,” “above,” “below,” and words of similar import, when used in this application, shall refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the above Detailed Description using the singular or plural number may also include the plural or singular number respectively. The word “or” in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

Moreover, conditional language used herein, such as, among others, “can,” “could,” “might,” “can,” “e.g.,” “for example,” “such as” and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states. Thus, such conditional language is not generally intended to imply that features, elements and/or states are in any way required for

one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without author input or prompting, whether these features, elements and/or states are included or are to be performed in any particular embodiment.

The above detailed description of embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise form disclosed above. While specific embodiments of, and examples for, the invention are described above for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. For example, while processes or blocks are presented in a given order, alternative embodiments may perform routines having steps, or employ systems having blocks, in a different order, and some processes or blocks may be deleted, moved, added, subdivided, combined, and/or modified. Each of these processes or blocks may be implemented in a variety of different ways. Also, while processes or blocks are at times shown as being performed in series, these processes or blocks may instead be performed in parallel, or may be performed at different times.

The teachings of the invention provided herein can be applied to other systems, not necessarily the system described above. The elements and acts of the various embodiments described above can be combined to provide further embodiments.

While certain embodiments of the inventions have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the disclosure. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the disclosure. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the disclosure.

What is claimed is:

1. An envelope tracking system comprising:

a power amplifier configured to amplify a radio frequency signal and to receive power from a power amplifier supply voltage; and

an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency signal, the envelope tracker including a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a second filter coupled between a DC voltage and the power amplifier supply voltage.

2. The envelope tracking system of claim 1 wherein the DC-to-DC converter is further configured to generate the DC voltage.

3. The envelope tracking system of claim 1 wherein each of the plurality of regulated voltages has a different voltage level.

4. The envelope tracking system of claim 1 wherein the modulator includes a plurality of switches each coupled between the modulator output voltage and a corresponding one of the plurality of regulated voltages.



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5. The envelope tracking system of claim 1 wherein the first filter includes at least one series inductor and at least one shunt capacitor.

6. The envelope tracking system of claim 5 wherein the first filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

7. The envelope tracking system of claim 1 wherein the second filter includes at least one series inductor and at least one shunt capacitor.

8. The envelope tracking system of claim 1 wherein the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter.

9. The envelope tracking system of claim 8 wherein the controllable delay circuit includes a plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

10. The envelope tracking system of claim 1 wherein a DC path through the second filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier.

11. A mobile device comprising:

a transceiver configured to generate a radio frequency transmit signal;

a front end circuit including a power amplifier configured to amplify the radio frequency transmit signal and to receive power from a power amplifier supply voltage; and

a power management circuit including an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency transmit signal, the envelope tracker including a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a second filter coupled between a DC voltage and the power amplifier supply voltage.

12. The mobile device of claim 11 wherein the DC-to-DC converter is further configured to generate the DC voltage.

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13. The mobile device of claim 11 further comprising a battery that provides a battery voltage, the DC-to-DC converter configured to generate the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage.

14. The mobile device of claim 11 wherein the first filter includes at least one series inductor, at least one shunt capacitor, and a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

15. The mobile device of claim 11 wherein the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter.

16. The mobile device of claim 15 wherein the controllable delay circuit includes a plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

17. A method of envelope tracking, the method comprising:

amplifying a radio frequency signal using a power amplifier;

supplying power to the power amplifier using a power amplifier supply voltage;

outputting a plurality of regulated voltages from a DC-to-DC converter;

generating a modulator output voltage based on the plurality of regulated voltages and an envelope signal using a modulator, the envelope signal corresponding to an envelope of the radio frequency signal;

controlling the power amplifier supply voltage using a first filter that is between the modulator output voltage and the power amplifier supply voltage; and

controlling the power amplifier supply voltage using a second filter that is between a DC voltage and the power amplifier supply voltage.

18. The method of claim 17 further comprising generating the DC voltage using the DC-to-DC converter.

19. The method of claim 17 further comprising providing DC blocking using a series DC blocking capacitor of the first filter.

20. The method of claim 17 further comprising controlling a relative delay between an AC path through the first filter and a DC path through the second filter using a controllable delay circuit.

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